TECHNICAL AND ECONOMIC ASSESSMENT OF REVERSE OSMOSIS FOR TREATMENT OF LANDFILL LEACHATE

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TECHNICAL AND ECONOMIC ASSESSMENT OF REVERSE OSMOSIS FOR TREATMENT OF LANDFILL LEACHATE

R. A. C. PROJECT NO. 303 RR

Prepared for
Waste Management Branch

by

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ABSTRACT

A multi stage treatment process for leachate from municipal landfill sites has been proposed and evaluated in laboratory scale experiments with samples of actual landfill leachate. The treatment process involves chemical precipitation of metals and other inorganic contaminants and microfiltration of the resulting solution to remove the precipitated metals and suspended solids. The filtered water is then processed in a reverse osmosis system to allow for discharge of a significant fraction of the water collected. Dissolved organics are concentrated and may be recycled or treated by conventional biological treatment processes.

Microfiltration (MF) experiments confirmed that metals an be removed and a suitable feed will be generated for subsequent reverse osmosis treatment at permeate reates consistent with similar MF applications of 2 - 4 $m^3/m^2/day$. Reverse osmosis (RO) tests confirmed that teatment can concentrate the remainning dissolved organics in a stream to be recirculated to the landfill site while allowing only 2% of the TOC to be discharged in the treated water.

The total cost for the process are somewhat more than for an activated sludge pocess but the precipitation/microfiltration process allows for efficient removal of metals from the leachate and will remain unaffected by variations in leachate characteristics.

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1.0 CONCLUSIONS AND RECOMMENDATIONS

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1.1 Conclusions

- Microfiltration softening of landfill leachate can remove virtually all the iron and suspended solids and reduce levels of other contaminants such as calcium (95%), magnesium (59%), and other heavy metals (chromium 84%, strontium 97%, and zinc 99%). This treated water is suitable for further treatment in spiral reverse osmosis systems or other processes for removal of residual organics.
- A flux of 4 m^3/m^2/day was achieved with the microfiltration membranes up to an 80% volume reduction using lime alone. The performance of the MF system is, however highly dependent upon the precipitation chemicals used and requires further optimization to determine the best conditions. The flux obtained when lime and soda ash were used as precipitation chemicals was somewhat lower.
- Reverse Osmosis was successful in removing 98% of the TOC and 98% of the conductivity from the pretreated feed.
- Four reverse osmosis membranes were tested. The Filmtec FT-30 RO membrane provided a flux between 0.5 and 0.65 $m3/m2$/day during the concentration test to a volume reduction of 50%. Flux rates and conductivity remained stable during the testing for the Filmtec membrane.
- Expected costs for the chemical addition, microfiltration, filter press and reverse osmosis stages of the process for

treating 57 to 170 m^3/day vary between $4.24 to $3.32 per m^3/processed, including amortized equipment and installation costs and operating costs.

- Operating benefits of the precipitation/microfiltration process include its ability to remove heavy metals and suspended solids and remain relatively unaffected by upset conditions which can affect the performance of conventional processes. Treated water is suitable for further treatment for removal of organics by reverse osmosis or possibly biological processes including recirculation or sewer discharge or even incineration.
- Other potential benefits of the reverse osmosis process include the reduced hydraulic load on downstream processes such as re on or hauling to sewer.
- The cost of the complete process using microfiltration (MF) and reverse osmosis (RO) are high relative to straight biological treatment and the process does require further treatment of residual organics in the RO concentrate. The removal of toxic metals from leachate may be a necessary step prior to biological treatment, recirculation or sewer discharge and the first stage microfiltration process can provide for effective removal of these contaminants.

1.2 Recommendations

- Results of the laboratory scale testing indicate that precipitation/microfiltration shows excellent potential for the removal of heavy metals and suspended solids from landfill leachates. The treated water will be suitable for further treatment of residual organics. It is, therefore, recommended that this treatment process be evaluated on continuous feed of leachate from a landfill site to determine operational and maintenance requirements (eg. membrane cleaning and long term flux) and to confirm treatment efficiencies for assessment of suitable downstream processes such as biological treatment, or reverse osmosis.

2.0 INTRODUCTION

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In recent years, the occurrence of a wide variety of organic and inorganic contaminants in ground and surface water has become recognized as a significant environmental concern by regulatory agencies. Many of the toxic and hazardous compounds commonly found in contaminated waters originate from landfill leachates, as a result of the soluble components of solid and liquid wastes contaminating surface and groundwater.

Often these landfill leachates are comparable to complex industrial waste streams. In cases where drinking water supplies may be impacted or where there is a surface breakout, remedial actions must be undertaken. At some landfill sites, the leachate is collected and discharged to municipal sewers for treatment in conventional sewage treatment processes. At other landfill sites where sewer lines are not available, the leachate water may be hauled off site for treatment, may be recycled back to the landfill site or may be discharged to a surface water source. Discharge of leachate to conventional sewers can be a problem because heavy metals and some complex organics are either not effectively removed by conventional municipal treatment processes, or they may contaminate the sludge produced. New MISA regulations may also limit the discharge of such complex wastes to municipal sewers. The process of hauling leachate for treatment by conventional processes is expensive. Recycling leachate within the landfill site itself can reduce the amount of liquid leaving the site for some time but cannot

provide a long term solution to the problem. On site biological process can reduce the levels of some organics but are not effective in removing refractory organics or metals and may be inhibited by the presence of toxic metals. Effective and inexpensive methods of treating leachate need to be developed.

ZENON has been contracted to assess the application of reverse osmosis (RO) technology for the treatment of landfill leachates and evaluate the technical and economic benefits of RO for treatment of this waste water. The scope of the technical assessment includes evaluation of pretreatment processes for use before RO, and evaluation of an RO test system to determine its efficiency in removing contaminants and other performance characteristics such as membrane flux. Technical advantages of this process are considered in light of the results of this experimental work. Capital and operating costs for the RO treatment process were also developed based on the results of the experimental work and compared with costs conventional treatment practices.

3.0 REVIEW OF TREATMENT TECHNOLOGIES AND LEACHATE CHARACTERISTICS

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3.1 Leachate Characteristics

Investigations of leachate composition have been conducted as early as the 1950's. A more recent study by Chian and DeWalle (1976) of the University of Illinois involved characterization of leachate samples obtained from laboratory scale (lysimeters), pilot-scale and field-scale sanitary landfills located throughout the United States. They also summarized previous work involving characterization of leachate from different sources by different researchers. Table 3.1 is an adaption of their summary showing results of five leachate characterizations from landfills of different ages. Chian and DeWalle (1977) also characte landfill leachate using ultrafiltration, gel permeation, gas chromatography and specific organic analysis and found that the lower molecular weight fraction contained carboxyl and aromatic hydroxyl groups, and colour while the higher molecular weight fraction contained carbohydrates and hydrolyzable amino acids. Analyses of samples from different environments indicated similar distribution and composition of the molecular weight fractions. They concluded that these similarities suggest that the chemical and bacterial processes occurring are the same. Slater, Uchrin and Ahlert (1985) confirmed Chian and DeWalle's work by characterizing landfill leachate which was separated into different molecular weight fractions by ultrafiltration. The fraction of the organic material below a molecular weight of 500 was composed of synthetic organics and common

Table 3.1
Composition of Leachate
(Chian and DeWalle, (1976))

Parameter	SHWRL	Georgia Tech	Du-page LW58	Du-page LW58	Du-page LW68
Landfill age, in years	1	3	5.5	8.5	16
COD	16,000-22,000	4320-12000	8000	2940	40
BOD	7500-10000	2500-11000	14000	4560	225
TOC		1230-5000			
pH	5.2-6.4	5.2-5.6	6.3		7.0
TS	10000-14000	2442-12500			
TDS	10000-14000		6794	5910	1196
TSS	100-700	34-610			
Specific Conductance	6000-9000				
Alkalinity ($CaCo_3$)	800-4000	558-2280	5810	4720	2250
Hardness ($CaCO_3$)	3500-5000	450-1940	2200	2250	540
Total - P	25-35	2.8-26	1.2	0.17	8.9
Ortho - P	23-33				
NH4 - N		56-187			
NO_3+NO_2-N	0.2-0.8		0.7	0.5	1.6
Ca	900-1700	125-750	308	447	102
Cl	600-800	98-385	1330	946	135
Na	450-500	64-143	810	615	74
K	295-310		610	220	100
Sulfate	400-650	81-156	2	1	2
Mn	75-125	3-10	0.06	0.09	0.06
Mg	160-250	26-75	450	725	90
Fe	210-325	9-95	6.3	12	0.6
Zn	10-30		0.4	0.05	4.5
Cu			<0.5	<0.5	<0.5
Cd			<0.05	<0.05	<0.05
Pd			0.5	1.0	1.0

industrial solvents containing aromatic and alcohol groups, such as phenols, amines, and chlorinated organics. The organics with a molecular weight of over 5,000 consisted of humic and fulvic substances, along with natural fermentation products. The majority of organic materials in the landfill leachate in this study was below a molecular weight of 500 indicating that the leachate was from a young landfill site. They concluded that leachate from older landfills would generally contain a higher proportion of organic compounds in a molecular weight range of 10,000 or greater.

Several factors affect the leachate composition. Initially, the origin and composition of the waste at the landfill site are the major factors. As chemical and bacterial processes occur, other factors such as the landfill site, the degree of compaction and the environmental conditions at the site (amount of precipitation and temperature), play a more important role. It is due to these factors that a range in the concentration of leachate constituents occurs (Boyle and Ham, 1974). The range of constituents in typical leachate is given in Table 3.2.

Chian and DeWalle (1976) analyzed results of leachate characteristics in terms of the ratios of parameters such as biological oxygen demand to chemical oxygen demand (BOD/COD), chemical oxygen demand to total organic carbon (COD/TOC), total volatile solids to total fixed solids (VS/FS), and sulfate to chloride (SO_4/Cl). These ratios revealed a general trend of decreasing concentrations with

Table 3.2
Composition of Typical Leachates
(Boyle and Ham, (1974))

Constituent	Concentration Range (mg/l)
Iron	200-1700
Zinc	1-135
Phosphate	5-130
Sulfate	25-500
Chloride	100-2400
Sodium	100-3800
Nitrogen	20-500
Hardness as CaCO3	200-5250
COD	100-51000
Total Residue	1000-45000
Nickel	0.01-0.8
Copper	0.10-9.0
pH	4.00-8.5

increasing age, as a result of anaerobic decomposition occurring within the landfill. During the first stage of anaerobic decomposition, complex organics are converted into organic acids. The total organic carbon (TOC) will remain substantially the same but the BOD and COD values will decrease due the more oxidized state of the organic carbon. High concentrations of organic acids, particularly butyric acids, indicate a high rate of first stage anaerobic decomposition.

Sulphate is reduced to sulfide and the existence of sulfide and carbonate causes dissolved metals to precipitate from solution. The ratio of volatile solids to fixed solids tends to decrease with age, since volatile solids decompose with age, while the concentration of metals decreases only due to washout and generally remains constant. Potentially toxic contaminants are present at each stage in the lifetime of the site and treatment of the leachate will be required through the lifetime of the landfill site.

3.2 Review of Treatment Technology

Many different treatment options have been investigated by researchers at universities and research centres for the treatment of landfill of leachate. Some of the treatment methods include:

Biological (Boyle, et al, 1984, Chian et al, 1976)

- recirculation, (Robinson et al 1985)
- aerated lagoons,
- activated sludge system,
- sequencing batch reactor (SBR), (Ying et al 1987)
- anaerobic lagoons,

- rotating biological contactors (RBC),

Physical/Chemical treatment (Bjorkman et al 1977)

- precipitation, (Chian et al 1976)
- coagulation, (Ho, et al 1974)
- oxidation and reduction, (Ho, et al 1974)
- activated carbon, (Parmele, et al 1986)
- microfiltration, (Tiepel & Shorr, 1985)
- ultrafiltration, (Syzdek et al 1984)
- reverse osmosis, (Chian et al 1976)

Other methods of disposal of leachate include:

- spray irrigation (McBride et al 1988)
- hauling to a sewage treatment plant and
- direct discharge.

Direct discharge of leachate to a water course may result in serious contamination of the environment by toxic metals and organics. The cost of the environmental damage and harm to human health is considerable and direct discharge is now being restricted by government regulations. Hauling of leachate to a sewage treatment plant involves considerable transportation cost and may be restricted in many locations because the toxic metals and refractory organics are not effectively removed by conventional biological treatment processes, or they may contaminate the sludge produced. The high strength wastes may also overload the capacity of sewage treatment plants.

Cost for hauling and sewer surcharges can be high. The Township of Mersea, Ontario for example pays $8.31/m3 for hauling their leachate to the local sewage treatment plant and a further $11.00/m3 for sewer surcharge. This does not include amortization of the capital cost for their leachate collection system. (Personal Communication - Tod Pepper, Township of Mersea, 1988).

Spray irrigation is another disposal option which has received considerable attention and can be conducted on land adjacent to the landfill site or off-site. The leachate is sprayed and dispersed over a large area of land. The volume of water present is reduced by evaporation and organics are reduced by natural biological activity and sunlight. This treatment is limited by climatic conditions as winter temperatures may result in freezing and heavy precipitation or overspraying may result in water logged conditions. Many organic contaminants may be degraded by natural biological activity and sunlight but metals and some refractory organics may cause long term environmental damage to the area used. Spray irrigation may also be limited by serious odour problems resulting from the process. (McBride et al, 1988).

Biological Treatment

The simplest biological treatment option involves recirculation of the leachate to the landfill itself. The landfill then acts as an anaerobic filter as natural biological activity degrades many of the organics present. Spraying combined with

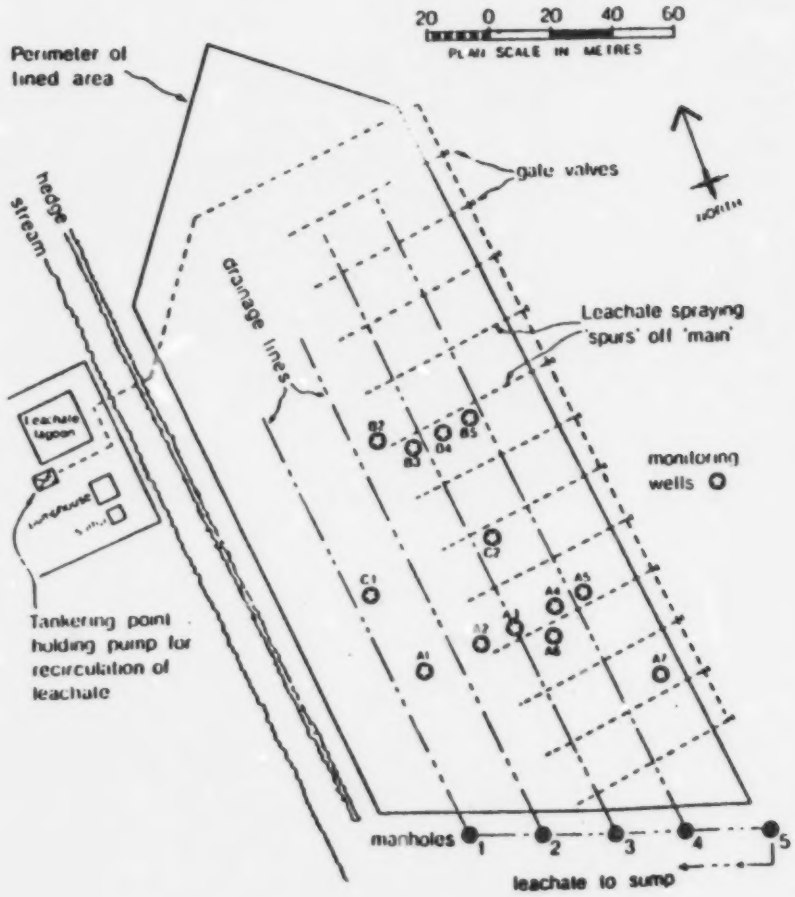
recirculation aids in reducing leachate volume by evaporation. Generally the landfill site is lined with an impermeable liner. Porous tile drains are placed on top of the liner and pulverized waste fills the site. Leachate, which collects in the base of the landfill, is then transported through the porous tile and drains to a sump where it is pumped to a storage lagoon. Leachate is pumped from the storage lagoon to a number of lines of tubing which are perforated on their upper sides. Leachate flows through the tubing to a sufficient height to give good distribution over the landfill site. Robinson and Maris (1985) utilized this method in a study and there was a resulting 40% reduction in COD over a 20-month period, however, ammonia and chloride concentrations did not decrease to the same extent. Figure 3.1 presents a schematic of the leachate collection and distribution system used in this study. The recirculation process is simple and inexpensive relative to some other processes if the required containment and collection systems are incorporated into the original site design. The process can suffer from reduced biological activity as a result of inhibition due to heavy metals and toxic organics present in the leachate. Recirculation is limited in its ability to remove heavy metals and refractory organics and may suffer from a buildup of excess water in the landfill itself. The process may not be acceptable if not all the leachate is collected as a result of leaks in the lining of landfill which allow heavy metals and other contaminants in the leachate to enter the environment.

Studies into the application of aerobic biological treatment

Figure 3.1

Schematic of Leachate Collection and Distribution System

(H.D. Robinson and P.J. Maris (1985))



include aerated lagoons and activated sludge-systems operated on a continuous-flow or batch mode. Leachate from young landfill sites (less than 5 years) generally has a high concentration of volatile fatty acids an is easily biodegraded resulting in significant reduction of BOD and COD. The addition of nutrients is often required to maintain the optimum ratio of BOD to nitrogen to phosphorus to 100/5/1. Leachate from older, more decomposed wastes contains a higher proportion of refractory organic compounds, such as humic and fulvic acids, which are not easily biodegraded.

Boyle and Ham (1974) at the University of Wisconsin investigated three types of aerobic biological units for treatment of leachate. Two units were operated on a fill and draw method with no settling and a detention time of five days. The BOD load to the units was varied. A reduction in BOD of 93% was achieved at a BOD loading of 0.58 kg/m^3/day (0.036 lb/cu.ft/day). A BOD loading of 1.4 kg/m^3/day (0.087 lb/cu.ft/day) resulted in a lower process efficiency of 80% BOD removal. The third unit was operated as an activated sludge process on a 23-hour cycle with one-hour of settling. The BOD load to the unit was very high at 5.2 kg/m3/day (0.33 lb/cu.ft/day) and virtually no BOD removal was achieved. Problems with solid/liquid separation resulted in high effluent solids concentration. Both modes of aerobic treatment encountered serious foaming problems and had high power requirements. There was also a slight deficiency in the nitrogen content for the desired BOD/nitrogen/phosphorus ratio of 100/5/1.

Robinson and Maris (1983) also performed laboratory studies applying aerobic biological treatment to leachate. Three sets of experiments were performed varying the solids retention time (SRT) from one to twenty days, the temperature from 10oC to 5oC, and the influent ammonia concentration. All experiments were operated in a continuous-flow mode in a 20-L continuously mixed and aerated reactor. Phosphate and antifoaming agents were added to diluted leachate before entering the reaction vessel. Results from experiments varying the influent ammonia concentration indicated that for successful nitrification, a high degree of control would be required. Changes in temperature affected the units operating at low SRT values the most but all units recovered at 10°C. An SRT value of five days produced erratic results and bulky, filamentous sludges. SRT values of 10 days provided 98% removal of BOD from settled effluent and 92% removal of COD. Heavy metals such as iron, manganese, and zinc were removed in the sludge probably due to the increase in pH to 8.5.

Studies at a hazardous waste treatment site in the U.S. have evaluated different treatment options. Shuckrow, Pajak, and Touhill (1986) investigated biological treatment utilizing biomass acclimated to raw contaminated groundwater in an activated sludge process. TOC removal ranged from 35% to 60%. An effluent TOC of 174 to 47 mg/L was achieved.

Slater, Uchrin and Ahlert (1985) pretreated landfill leachate by lime-coagulation and recarbonation, followed by

ultrafiltration. The leachate was then subjected to aerobic biodegradation which reduced the overall TOC by 62%, a predominant portion consisting of the low molecular weight fraction.

Problems associated with the activated sludge process include hydraulic and organic overloading, lack of nutrient additions and inadequate aeration (Robinson and Maris, 1983). Heavy metal concentrations may also upset biological treatment processes (Boyle and Ham, 1974). Reliable steady state conditions cannot be obtained with the seasonal variation in leachate composition and necessitate dilution of the leachate to a set COD or BOD value. One potential solution to the problem of seasonal variation in leachate composition is a combined treatment of leachate and primary treated wastewater. Kelly (1987) pilot tested this combined treatment in Chilliwack, British Columbia. A pilot plant consisted of a test and control train. Each train had three 45-gallon drums operating as two aeration tanks and a final clarifier. The pilot plant was operated for 77 days with 2, 4, and 16% of the volume consisting of leachate. This influent composition did not introduce instability to the system. A C reduction of 69% was achieved with a feed consisting of 16% volume of leachate. Comparison of test and control train results indicated that with addition of leachate in the feed COD removal deteriorated, sludge production increased, and a higher metal concentration was observed in the sludge produced. They concluded that new sludge handling processes would be required as a result in changes in sludge characteristics. The levels of heavy metals in the leachate and hence sludge produced from

landfills serving major industrial cities will be significantly higher than those serving small urban agricultural centres.

Anaerobic biological treatment generally consists of a large storage lagoon to allow the leachate to biodegrade. Problems associated with this treatment include the large area required and the potential odour problems associated with reduced sulphur compounds (Harrington and Maris, 1986). Boyle and Ham (1974) studied anaerobic biological treatment on a laboratory scale. The initial study involved two bench-scale glass reactors with feed, draw off, and gas collection lines, operated on a fill and draw basis, being fed every 24 hours for a seven month period. Analysis of the supernatant indicated that greater than 90% BOD reduction was achieved at loadings of 0.85 to 1.05 kg/m^3/day (0.053-0.0[illegible]^3/day) and a 10-12 day detention period at a temperature of 23 to 30°C. Aerobic polishing, following this treatment, indicated a further 70% of the BOD and 40% of the COD could be removed. A decrease in temperatures between 23°C and 11°C was found to decrease the rate of anaerobic stabilization of BOD present in the leachate.

Physical and Chemical Treatment

Physical and chemical treatment methods which have been applied to the treatment of landfill leachates include: precipitation, coagulation, oxidation and reduction, activated carbon, microfiltration, ultrafiltration and reverse osmosis. Ho, Boyle, and Ham (1974) performed several laboratory scale tests applying

physical-chemical treatment to landfill leachate. Chlorine, calcium hypochlorite, potassium permanganate, and ozone were investigated as possible chemical oxidants. The COD removals obtained were 25% with chlorine, 20% with potassium permanganate, 37% with ozone, and 48% with calcium hypochlorite. All oxidants provided good iron and colour removal and little sludge was produced with ozone or calcium hypochlorite. Coagulation with alum and ferric chloride also removed iron and colour, however, virtually no COD was removed using alum, whereas ferric chloride achieved 16% COD removal. In chemical precipitation tests, lime and sodium sulfide were tested. Both removed iron and colour, lime to a greater extent than sodium sulfide, but neither removed significant amounts of COD.

Chian and DeWalle (1976) found that lime coagulation was able to remove the organic matter having a molecular weight greater than 50,000. This fraction tends to be present in landfill sites which have been in operation for 5-10 years but very low in sites less than 5 years old or older than 10 years. Organic removal by coagulation is poor in these younger or very old sites.

Activated carbon has also been investigated to treat landfill leachates by Bjorkman and Mavinic (1977) who found that 34-59% removal of COD could be achieved. Ho, Boyle and Ham (1974) were able to remove 55% COD and greater than 60% of iron after 22 minutes detention time. A further study by Uloth and Mavinic (1977) showed that lime pretreatment before treatment by activated carbon resulted in

81% COD removal. Activated carbon is effective in removing many organics which are difficult to degrade biologically and may be used in combination with biological processes.

Millot et al (1987) investigated three different treatment processes for landfill leachate, including aerobic biological treatment, physical-chemical coagulation-flocculation and activated carbon. They found that biological treatment was effective in eliminating compounds with a low molecular weight which consisted of volatile fatty acid, but was not effective on compounds with a molecular weight greater than 5,000. Coagulation-flocculation was found to effectively treat these compounds, and a final treatment by activated carbon was able to remove the remaining compounds.

Generally physical-chemical treatment is limited in its application to landfill leachates. Precipitation and coagulation provide good removal of iron, heavy metals and colour but do not remove organic material to a significant degree. Oxidation provides for a better removal of organic but is still not an effective treatment method because fatty acids are not amenable to oxidation. Chemical precipitation, coagulation, and oxidation all require high chemical dosage rates and therefore result in production of sludge, and the operating costs are high. Chemical treatment requires only simple equipment, is not affected by seasonal changes in temperature, and can be easily automated. Activated carbon can be used to reduce COD levels in leachate but the removal efficiency is affected by the nature of the

organics present. Young landfills generally contain a large proportion of small molecular weight volatile acids which are not removed by activated carbon as effectively as higher molecular weight organics. Activated carbon suitable for treatment of only certain types of organics and may be used as one unit operation in a multi-step treatment process.

Ying and Bonk (1987) investigated two integrated bio-physical wastewater treatment processes; 1) sequencing batch reactors (SBR) followed by activated carbon adsorption and 2) sequencing batch reactors with powdered activated carbon (PAC). Currently leachate from the Hyde Park Landfill site in New York State is being collected and pumped to a two-compartment lagoon. Gross solids are removed by gravity separation and the supernatant is trucked to a wastewater treatment plant in a nearly chemical plant. Leachate is mixed with plant wastewaters, the pH is adjusted, sus solids are removed by clarification and filtration and the filtrate is treated in a two-stage activated carbon adsorption system. The effluent is then discharged to a municipal sewer. The two proposed treatment schemes were studied for treating the combined wastewater to increase the efficiency of carbon utilization. Sequencing batch reactor (SBR) biotreatment is a fill-and-draw activated sludge process in which all the treatment stages: fill, react, settle and draw occur in one tank. The wastewater is first fed to system. Aeration, mixing and destruction of biodegradable organics occur during the next phase. Clarification occurs in the same tank and the supernatant is withdrawn during the

final phase. The SBR process was operated with the clarified wastewater feed and the treated water was fed to the carbon adsorption process for removal of residual refractory organics. The use of this biological treatment prior to carbon adsorption reduced the carbon requirement by 90% since a substantial amount of the organic contaminants present were removed prior to the carbon process. The SBR process was then operated as before but powdered activated carbon (PAC) was added to the SBR near the end of aeration step. The dosage of PAC was 3 gm/L. The PAC-SBR process was effective in removing organic contaminants including halogenated organic compounds. The use of PAC in the SBR eliminated the need for final polishing by activated carbon. The large amount of PAC in the mixed liquor prevented adverse effects due to sudden changes in wastewater characteristics. The authors concluded that the rocess costs would be lower than SBR followed by activated carbon.

Researchers in the United Kingdom (Harrington, et. al., 1988) presented capital and operating costs for different treatment processes for leachate treatment. The costs for land irrigation, activated sludge and extended aeration processes are presented in Table 3.3. The costs were converted from British Pounds and updated to 1988 Canadian Dollars. The total cost per cubic meter of leachate is also presented based on 10 year amortization of capital costs at 11% interest and operating costs. The cost for land irrigation is the lowest at only \$0.36 per m^3. The report suggests that the costs for recirculation of leachate would likely be similar. The cost for the

Table 3.3
Leachate Treatment Costs
(Harrington et. al., 1986)

Treatment Process	Capacity (cu. m./day)	Capital Cost ($)	Yearly Operating Costs ($)	Total Costs ($ / cu. m.)
Land Irrigation	90-136	$26,288	$4,015 - $12,410	$0.36
Activated Sludge	20-150	$224,690	$8,213 - $90,155	$2.95
Extended Aeration	100	$103,356	$16,425	$0.93

Total Costs Include Capital Costs Amortized Over 10 years at 11 % interest and Operating Costs.

All Costs in 1988 Canadian Dollars.

two biological processes of activated sludge and extended aeration differ considerably at $2.95 per m^3 and $0.93 per m^3.

Cross Flow Filtration Processes

Cross flow membrane filtration processes including microfiltration (MF), ultrafiltration (UF) and reverse osmosis (RO) have been applied to the treatment of a wide variety of industrial waste water streams. Some of these include wastewater from electroplating, petroleum, petrochemical, pulp and paper, food and beverage plants. Microfiltation processes with a filtration size of 0.1 to 1.0 microns remove suspended solids which are not easily settled and have been applied to the treatment of many contaminated wastewaters as the solids removal step after chemical precipitation of toxic metals. The MF process provides [illegible]ured discharge water quality and is less susceptible to upset conditions than conventional solids removal processes and is not affected by poor settling characteristics of the solids produced.

Ultrafiltration processes which operate in a smaller filtration range (0.002-0.1 microns) are commonly used for the concentration of wastewater containing emulsified oils or large molecular weight organic contaminants.

Reverse Osmosis processes with a filtration range of less than 0.002 microns are used for the removal of dissolved solids and

organic contaminants. Considerable work has been done evaluating the use of RO for the removal of problematic compounds in a variety of waste streams. Researchers have investigated the possibility of using RO for the treatment of landfill leachates.

All cross flow filtration systems are affected by variations in operating temperature. Membrane throughput or flux will generally increase with increasing temperature up to the maximum operating limitations of the membrane. An increase in temperature from 25°C to 35°C may result in as much as a 36% increase in flux for some RO systems.

Ahlert and Syzdek (1984) at Rutgers University tested nine different ultrafiltration membranes on a pretreated leachate. Operating variables such as pressure, leachate strength and shear rate (controlled by the stirring rate at the membrane surface) were varied to control fouling of the ultrafiltration membranes. They concluded that ultrafiltration can be included as one process in the treatment train of landfill leachates.

Slater, Ahlert and Uchrin (1983) were able to effectively remove high concentrations of inorganic and organic matter from pretreated industrial landfill leachate using tubular reverse osmosis cellulose acetate membranes. Pretreatment consisted of addition of lime to the raw leachate to remove turbidity, heavy metals and suspended and colloidal matter. Reverse osmosis treatment was able to

remove 98% of the TDS, 68% of the COD, and 59% of the TOC producing an effluent with 340 mg/L of TDS, 8,570 mg/L of COD, and 3,440 mg/L of TOC. The membrane flux rate averaged 0.18 $m^3/m^2/d$ (4.4 USgfd). A later study involved a more extensive pretreatment system consisting of a physiochemical process using lime coagulation followed by recarbonation, biological treatment and filtration prior to the RO system. TDS was reduced to 47.2 mg/L, and TOC was reduced to 14 mg/l with a 66% volume reduction in the RO process.

Chian, Fang, and Bruce (1975) studied the removal of pesticides by reverse osmosis. Water contaminated with thirteen pesticides, including chlorinated hydrocarbons, and other pesticides was tested. Two membrane types, including cellulose acetate and cross-linked polyethylenimine, were evaluated for their removal efficiency. The test was conducted in a static test cell operated at 600 psig. The reverse osmosis membranes were able to remove 99.5% of the nonpolar pesticides, but the removal of the polar pesticides was less satisfactory.

In Canada, Environment Canada has investigated RO for the treatment of dilute landfill leachate, chemical spill clean- up and industrial waste processing. In one such test by Whittaker and Szaplonczay (1985), 18 model compounds were chosen from a list of commonly spilled hazardous chemicals and spiked solutions were tested in a mobile RO unit with four spiral wound membranes. The researchers concluded that reverse osmosis can be successfully used to remove many

commonly spilled chemicals from contaminated waters. Straforelli and Whittaker (1985) investigated the application of reverse osmosis to spilled chlorophenol solutions, which are utilized in the wood preservation industry. The feed concentration of chlorophenol ranged from 3.0 to 2,000 mg/L, and an effluent concentration of 0.03 to 0.04 mg/L total chlorophenols was consistently produced. When used in combination with granular activated carbon, an influent concentration of 1.3 mg/L chlorophenol was reduced to 0.0017 mg/L chlorophenol. This level was below the target for British Columbia drinking water of 0.002 mg/L.

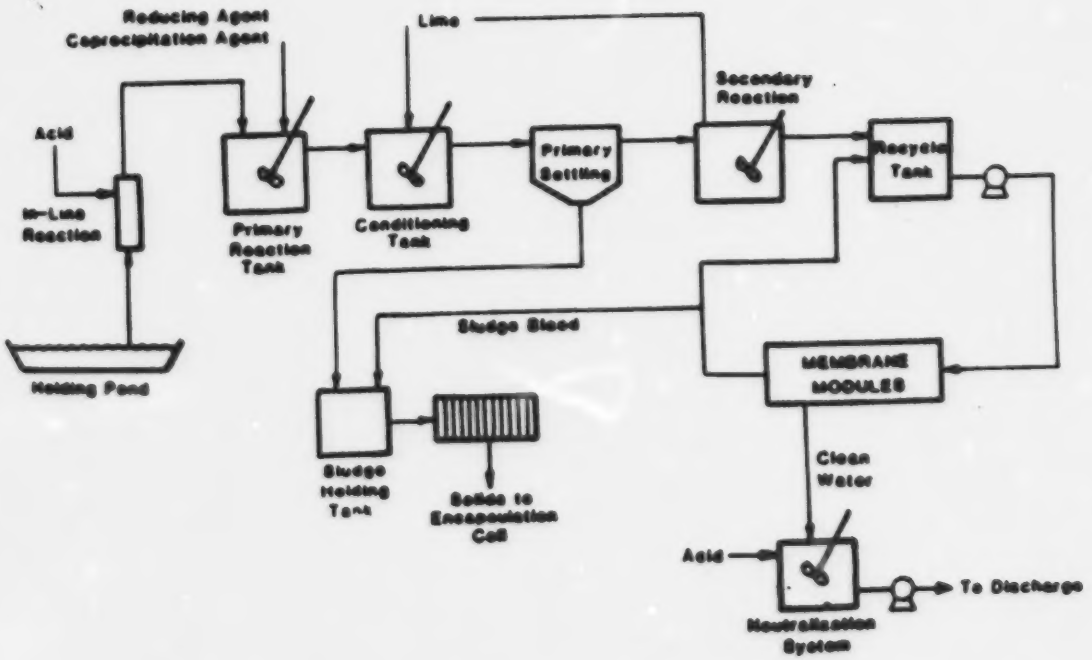
Successful removal of PCBs from leachate using reverse osmosis was demonstrated at the MacDonald landfill in Amherst by Environment Canada (Whittaker and Tremblay, 1985). Further studies on the treatability of leachate from a landfill containing hazardous wastes were conducted by (Whittaker et al, 1985) Environment Canada at the at Gloucester landfill site in the Ottawa region. This study demonstrated that high rejection of low molecular weight organics was possible with RO.

Precipitation-microfiltration (PPT/MF) processes have been used for the removal of toxic metals in the metal finishing industry. Researchers in the United States have also used this process of chemical pretreatment followed by cross flow microfiltration for treatment of contaminated tailings pond water (Tiepel and Shorr, 1984). Figure 3.2 shows a flow schematic of the treatment process. Uranium,

Figure 3.2

Schematic of Chemical Pretreatment and Filtration Treatment Process

(E.W. Tiepel and J. Shorr)

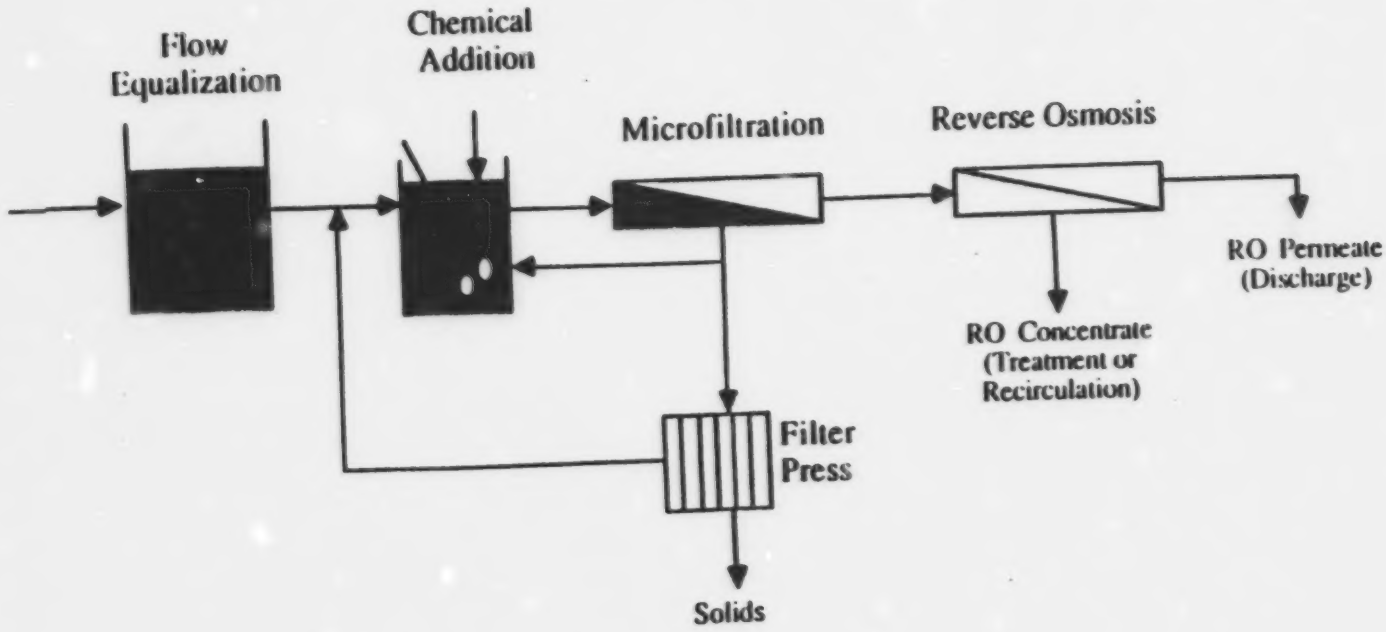


radium, selenium, arsenic and other metals are precipitated by reaction with lime. The bulk of the solids are removed in a gravity settler and microfiltration is used to insure that no residual precipitated metals are discharged with the treated water. In test work the process was found to be effective in removing precipitated contaminants and a flux rate of 10 $m^3/m^2/day$ (250 USgfd) was obtained.

The complex nature of landfill leachates necessitates a treatment proces able to treat both inorganic and organic contaminants, thus an integrated treatment scheme has been proposed in this study. Precipitation of metals with lime and soda ash followed by microfiltration to remove suspended solids and precipitated materials is performed to remove heavy metals as hydroxides, lower the turbidity, hardness and iron, and remove some of the less soluble organic material. The permeate from the MF process still contains the soluble organic components which can be concentrated by reverse osmosis or treated in a biological treatment process. If RO is used to concentrate organics one stream containing clean water with very low levels of small molecular weight organics and one stream containing concentrated organics contaminants and residual dissolved solids will be generated. The concentrated organics may be recycled back to the landfill site where natural biodegradation will breakdown the organics present. Alternately, the concentrate may be treated in an on-site biological process or hauled to off site treatment. A schematic of this potential process is shown in Figure 3.3.

FIGURE 3.3

Microfiltration / Reverse Osmosis Process For Leachate Treatment



The potential benefits of the precipitation- microfiltration process over conventional precipitation settling processes include the ability of the process to completely remove toxic heavy metals and remain insensitive to upset conditions such as the settling characteristics of the solids formed. The microfiltration process is also compact in size relative to conventional clarifiers. The treated water from the MF will be more suitable for discharge to conventional sewage treatment or other process such as recirculation or land irrigation since the toxic metals and suspended solids will have been removed. The process can be modified to include activated carbon which will allow for the removal of many of the toxic organic contaminants as well. The potential benefits of using reverse osmosis include the reduced hydraulic loading on downstream processes and generation of a low dissolved solids clean water product stream. The reduction in hydraulic loading may be of significant benefit when recirculation, hauling to sewer or incineration are used for disposal of the residual organics.

4.0 EXPERIMENTAL PROCEDURE

4.0 EXPERIMENTAL PROCEDURES

4.1 Analysis Performed

Extensive analysis was done on samples of the raw feed, leachate treated by microfiltration and the RO permeate to characterize these streams to determine how they compare with the surface water discharge restrictions. Analysis performed included pH, total suspended solids (TSS), total dissolved solids (TDS), turbidity, conductivity, alkalinity, calcium and magnesium (Ca and Mg), total organic carbon (TOC), total organic halogen (TOX), organics by gas chromatography/flame ionization detector (GC/FID). Further characterization included biological oxygen demand (BOD), chemical oxygen demand (COD), volatile organics by gas chromatography/mass spectrophotometer (GC/MS) - (EPA method 624), extractable organics by GC/MS - (EPA method 625), anion, and cation scan.

More routine analysis generally consisted of pH, TSS, TDS, turbidity, conductivity, TOC and TOX to compare the quality of the permeates with each other. Detailed methodology for all analyses is given in Appendix A.

4.2 Microfiltration Experiments

4.2.1 Microfiltration Screening (Tests #1, 2 and 3)

Pretreatment screening tests were conducted to determine the pretreatment method most suitable prior to reverse osmosis. Selection

of the pretreatment method was based on the analytical results of the permeate and membrane flux rates obtained using three different chemical precipitation methods. The three precipitation methods evaluated included addition of caustic (NaOH) to pH 10, addition of lime to pH 10, and addition of lime to pH 10 and powdered activated carbon (PAC).

The apparatus used in these tests consisted of a 50 L (13 USgal) stainless steel tank, a multistage centrifugal pump, a tubular membrane test module, and associated tubing, valves, and pressure gauges. A schematic of the test apparatus is shown in Figure 4.1. The tank was equipped with a cooling jacket for temperature control. An in-line temperature probe near the outlet of the tank sent a signal to a cooling water con e. The system temperature could be monitored by an in-line probe thermometer on the outlet line from the pump. The flow rate to the tubular membrane module was controlled by adjusting flow through a bypass valve. A pressure gauge was mounted on the line to the membrane module to monitor the inlet pressure. The tubular membrane module consisted of six stainless steel support tubes each 1.27 cm (0.5 in) diameter by 32.9 cm (12 in) long. A schematic of the membrane module is given in Figure 4.2. This allowed six membranes to be tested under the same test conditions. A pressure gauge and needle valve on the outlet line of the membrane module monitored and controlled the back pressure. Valves were installed on the return line to allow the concentrate to be redirected to a flowmeter to enable direct measurement of the flow coming out of the membrane module.

FIGURE 4.1

Flow Schematic of Microfiltration Test Equipment

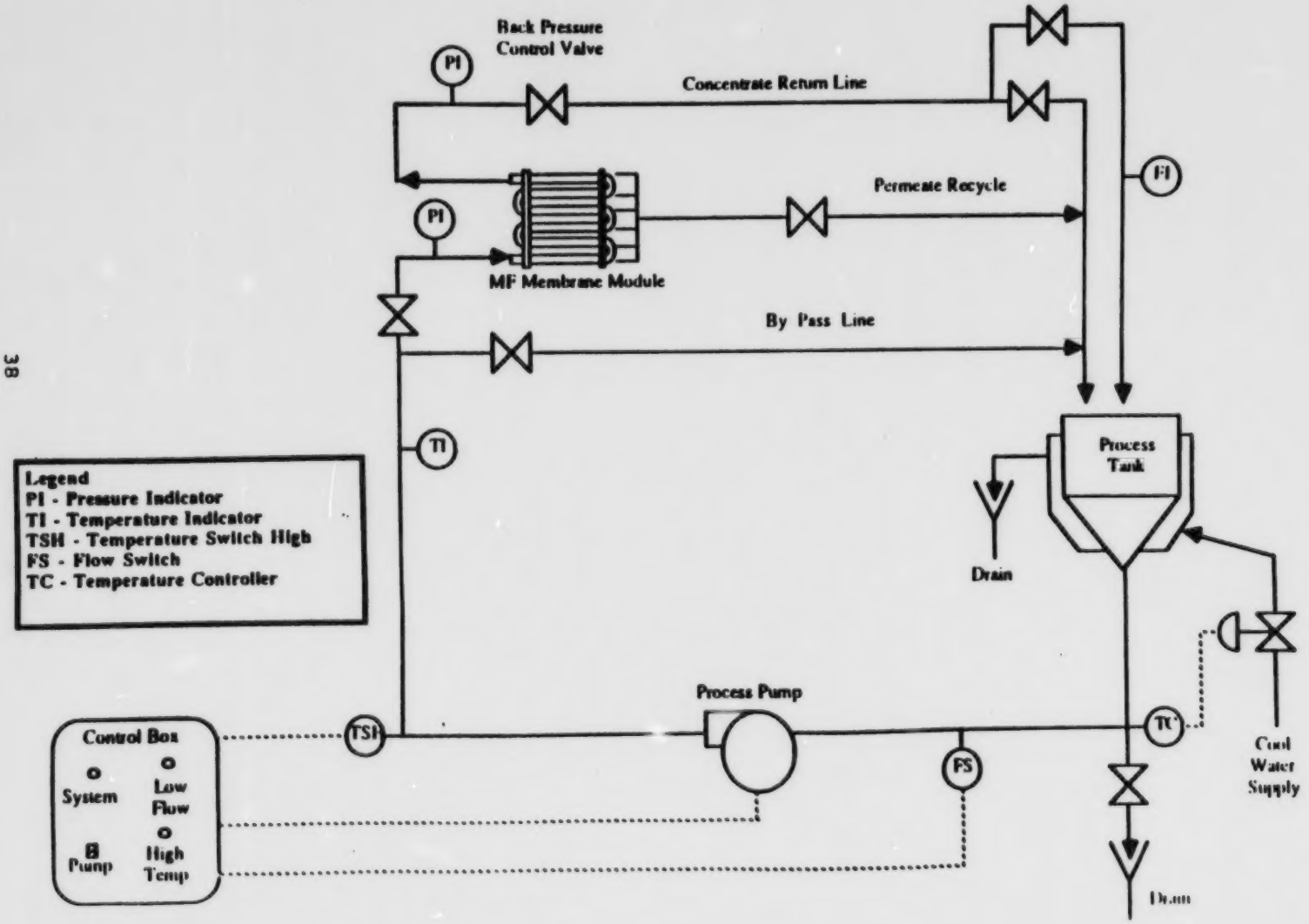
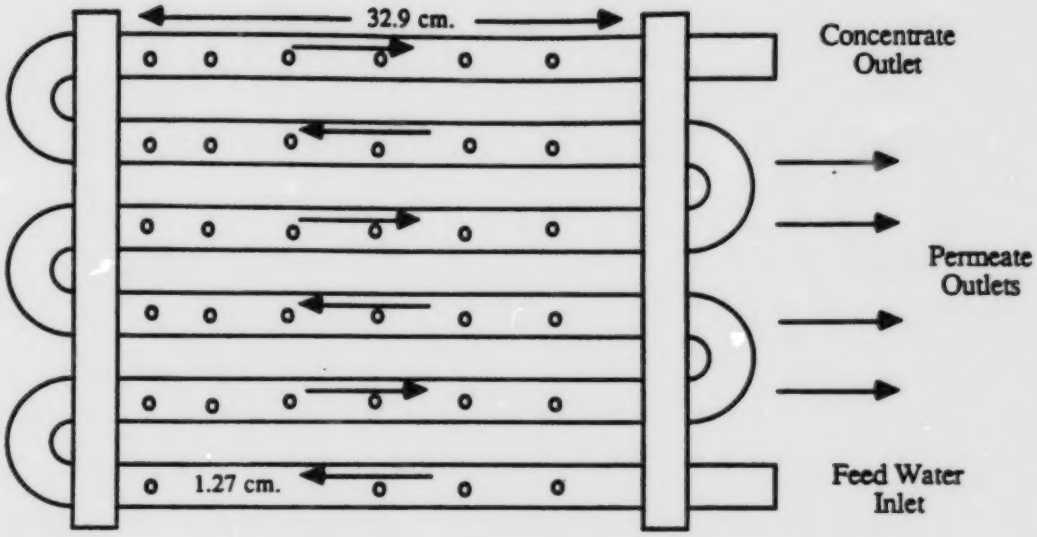
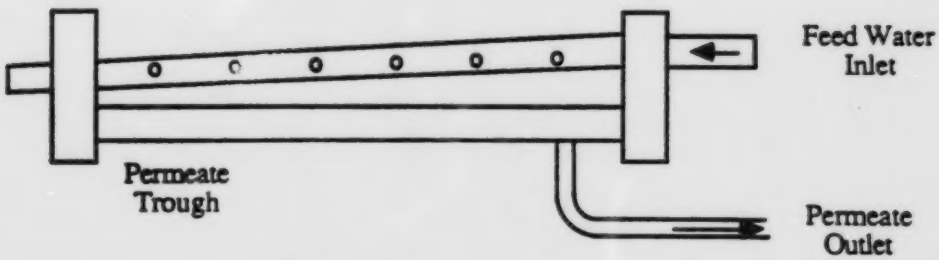


Figure 4.2

Tubular Membrane Test Apparatus



Top View



Front View

The membranes manufactured by ZENON Environmental Inc. were installed in the membrane test apparatus. Approximately 30 L (7.9 USgal) of raw feed was placed in the system feed tank. Caustic, lime and/or powdered activated carbon was added to the raw feed and mixed by recirculating the fluid through the pump. After pH adjustment was complete, flow was directed to the membrane test module and the inlet and outlet pressures were adjusted to 227 kPa (33 psi) and 172 kPa (25 psi) respectively. The flow through the membranes was set at 12 Lpm (3 USgpm) and the system temperature maintained at 25°C. These operating parameters were recorded approximately every 1/2 hour and permeate flowrates were recorded approximately every 10 minutes. The unit was run for one hour to ensure stability of the system, then run for a further 2-3 hours to collect permeate samples and additional flux data.

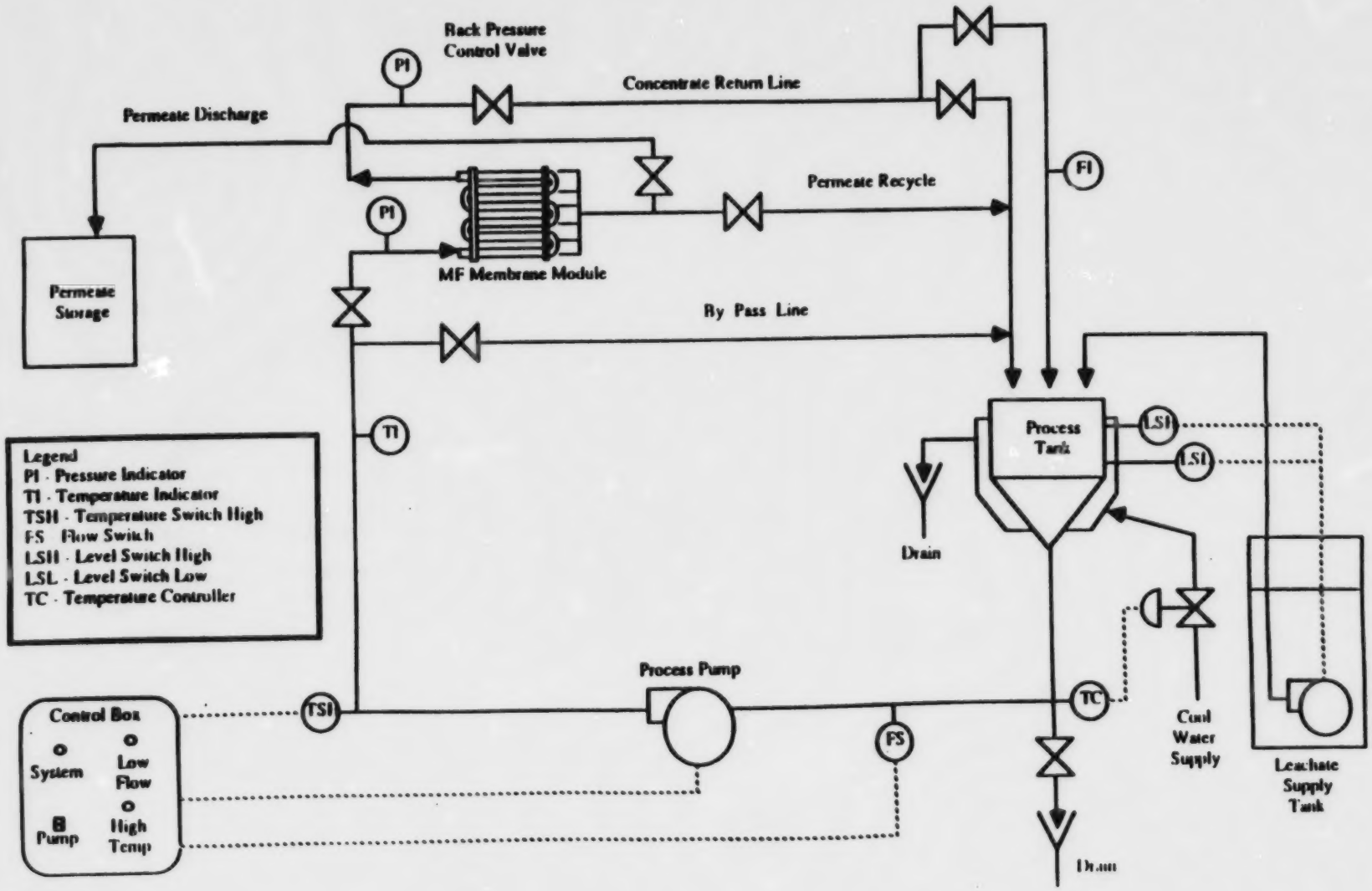
A sample of the raw feed was taken on the last day of testing. Permeate samples were taken after each test.

4.2.2 Large Volume Microfiltration (Tests 4 and 5)

During Test Number 4, two 200-L (53 USgal) drums of landfill leachate were treated using lime to pH 10. The test system was modified to allow for processing of a larger volume of wastewater in a batch concentration mode. Figure 4.3 shows a schematic of the modified bench scale membrane test apparatus. The pH of the feed was adjusted to 10 by addition of lime to the leachate in the storage drum.

FIGURE 4.3

Flow Schematic of Microfiltration Test Equipment



The drum contents were mixed using a submersible pump. During processing, the permeate was collected in a clean 200 L (53 USgal) container. The level of leachate in the feed tank was maintained using high and low level switches in this tank which activated a submersible pump located in the storage drum.

Samples of the feed, concentrate and permeate were taken to determine the removal efficiency of the MF process.

For Test Number 5, a fresh 200-L drum of landfill leachate was obtained. The pH of the feed was adjusted to 10 by addition of a 30% lime slurry. A lime slurry was used to increase the rate of contact between the leachate and lime. This solution was allowed to mix overnight. In Test Number 5, sodium carbonate (soda ash) was also added to the leachate along with lime to react with the residual calcium in solution to form insoluble calcium carbonate which would then be removed in the microfilter. This lime and soda ash process is similar to that used in lime softening processes. The leachate was processed in a batch concentration mode using the same procedure as the previous MF test.

Samples of the feed, concentrate, and permeate were collected to determine the removal efficiency of the MF process using lime and soda ash as precipitation chemicals.

4.3 Reverse Osmosis Experiments

4.3.1 Flat Sheet Reverse Osmosis Screening Test

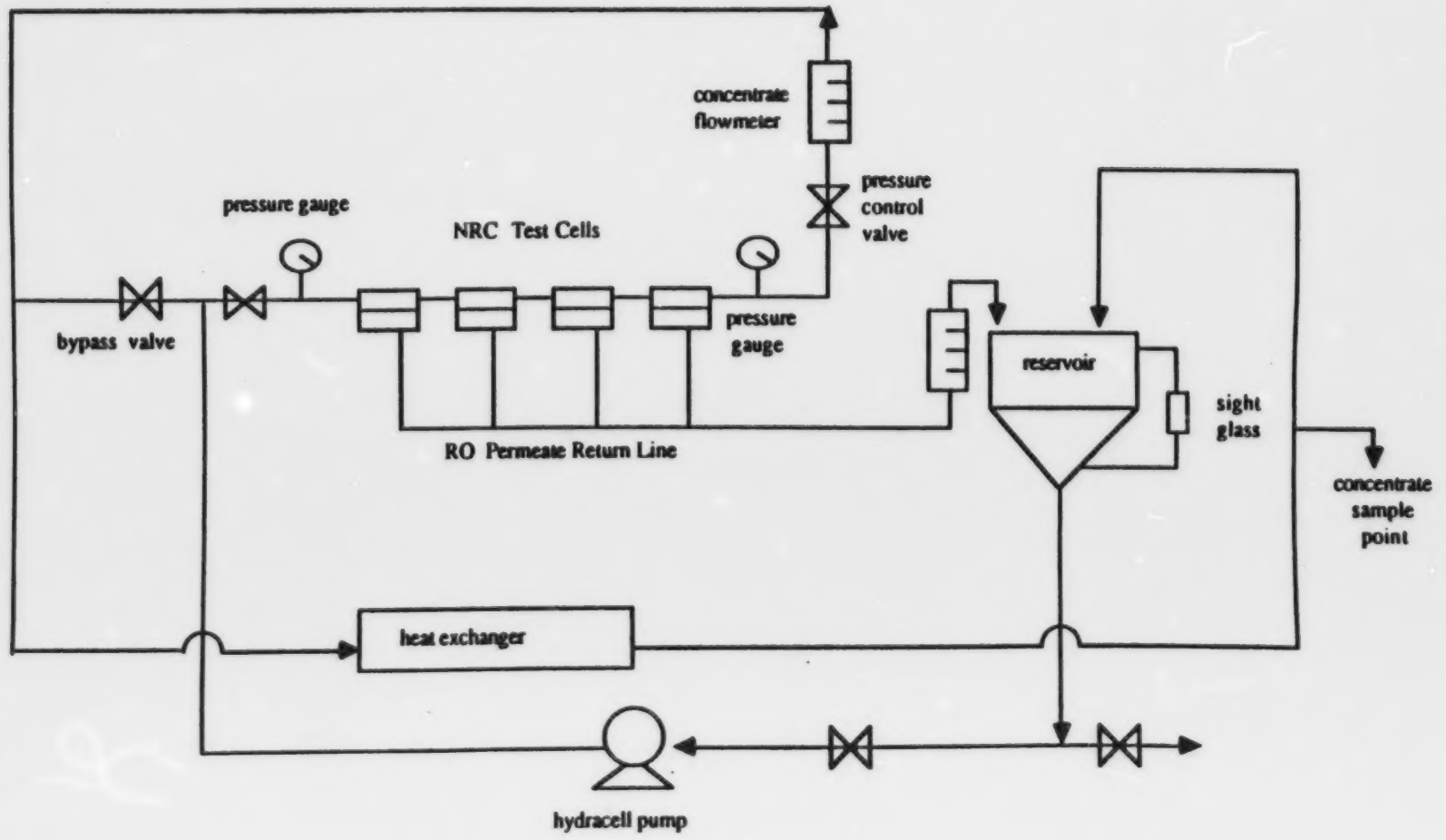
Reverse Osmosis membrane screening tests were conducted to determine the best membrane for use in this application. Flat sheet membranes were evaluated based on permeate quality and flux. Testing consisted of a stability test using the MF permeate as a feed and saltwater flux tests before and after the stability test. The four flat sheet membranes tested were Filmtec BW30, Desal 3LP, Toray PEC 1000, and Nitto-Denko NTR-739 HF.

The bench scale membrane test apparatus is shown in Figure 4.4. The test apparatus consisted of four small flat sheet membrane test cells, a 40-L (10.5gal) reservoir, a high pressure pump, a heat exchanger, and the necessary piping, fittings, and gauges. Initially, the inlet valve to the high pressure pump and the bypass valve were fully open. The pump was turned on and the inlet pressure was increased to 2,758 kPa (400 psi) by adjusting the back pressure and bypass valves. A pressure gauge mounted on the inlet to the first flat sheet cell and the outlet from the last cell measured the inlet and outlet pressure of the test cells.

The flow of the permeate and concentrate were each measured on a rotameter. To maintain a constant temperature throughout each test the concentrate passed through a heat exchanger before returning to the

Figure 4.4

Flow Schematic of RO Screening Test Equipment



feed tank. The level in the feed tank was indicated in a "sight glass" connected to the bottom and top of the reservoir.

Initial Saltwater Test

The initial saltwater test established an initial permeate flowrate and salt rejection under standard conditions of 420 psi applied pressure and 70°F. A 2,500 mg/L salt solution was prepared and poured into the reservoir. The test was run for three hours to ensure that the flux and rejection had stabilized. The temperature, concentrate and permeate flowrates, and feed and permeate conductivities were recorded at regular intervals.

Stability Test

A stability test was done to determine the performance of membranes with leachate treated by microfiltration. Thirty litres of MF permeate from MF Test Number 4 was transferred to the reservoir and the pH was adjusted to approximately five by the addition of concentrated hydrochloric acid. The flowrate and conductivity of the concentrate and permeates were recorded. Samples of the permeate and feed were obtained for analysis of TOC, and specific organic contaminants. The test was run for 91 hours in order to collect enough permeate samples for analysis.

Final Saltwater Test

The final salt-water test was conducted to indicate whether the flat sheet membranes had been affected by the test. The procedure

used was identical to that used in the initial saltwater test.

4.3.2 Spiral Reverse Osmosis Membrane Testing

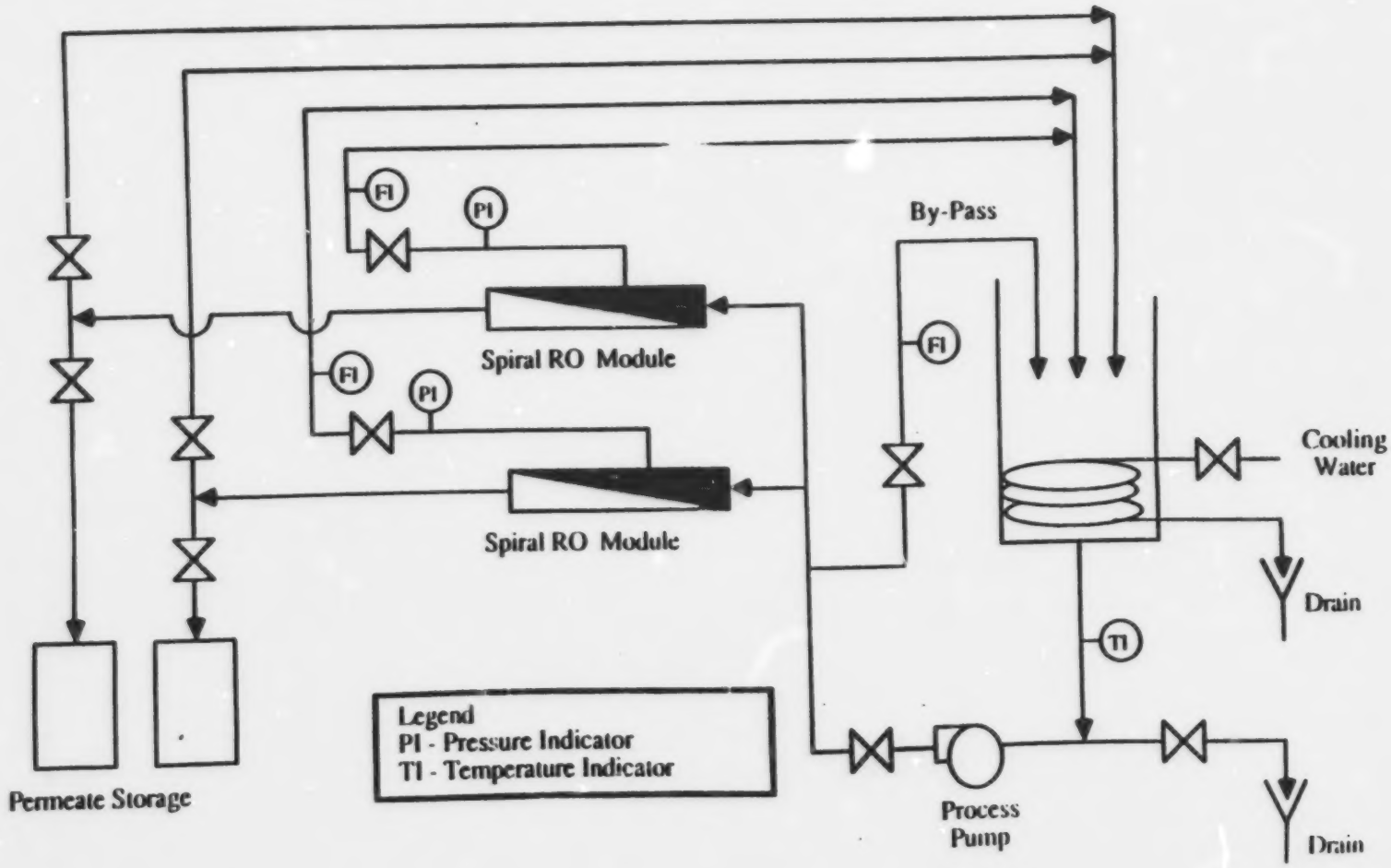
Based on the results of the flat sheet RO Screening test, two RO spiral membranes were obtained and tested in a pilot scale system to assess the performance under conditions similar to full scale operations, determine design information for system costing, and assess treatment efficiencies of reverse osmosis.

To assess the ability of the RO membranes to reject organics, the microfiltration permeate sample from MF Test Number 5 was spiked by addition of 1 mL of toluene and 0.75 g of pentachlorophenol to approximately 170 litres of microfiltration permeate. The leachate was adjusted to a pH of 5.5 by addition of concentrated hydrochloric acid.

The pilot-scale test apparatus is shown in Figure 4.5. The test apparatus consisted of two configured RO modules placed in parallel, a 200-L (53 USgal) feed tank, cooling coils placed within the tank, a high pressure pump and the associated piping, fittings and gauges. Operation of the test apparatus was initiated by opening the inlet valve to the Hydracell pump, the bypass valve, the outlet valves from the membranes, and the valve for the cooling water to the cooling coils. The pump was turned on. The feed flow and pressure for each membrane was kept below the maximum operating pressure specified by the

FIGURE 4.5

Flow Schematic For Reverse Osmosis Test Equipment



manufacturer by adjustment of each membranes outlet valve and the system bypass valve. The flow of the permeate and the concentrate were each measured. A cooling coil located in the feed tank was used to maintain a constant temperature throughout each test. The two spiral RO modules used in the testing were Filmtec BW30-2514, and Nitto-Denko NTR-729HF-52B.

Saltwater flux tests were conducted before and after testing to established initial and final permeate rates and salt rejection under standard conditions. The tests indicated whether the RO membranes had been affected by the test. The procedure was identical to salt flux tests conducted previously.

Initially, a stability test was done to determine the membranes performance on permeate from MF test #5. Approximately 40 L of leachate was transferred to the feed tank. The flowrate of the concentrate and permeate, and the conductivity of the feed and the permeate were recorded. Samples of the feed and permeate were obtained for analysis of TOC and TOX. The test was run for one and three quarter hours.

A batch concentration test was run to a volume reduction of 50%. Eighty liters of the leachate was pumped to the feed tank. The test system was started and the pressure and flowrates adjusted by the outlet and bypass valves. Permeate from each membrane module was collected in 20-L pails. Permeate flowrates and conductivities were

recorded approximately every 10 minutes. When a 50% volume reduction was reached, the permeate line was again returned to the feed tank and a stability test continued for another three hours.

After the first batch concentration, the membranes were washed using a nonionic alkaline detergent. Approximately 300 ml. of the cleaner was added to 60 L of deionized (DI) water. The test system was started and the cleaning solution recirculated through the membranes under no pressure for 10 minutes. The pump was turned off and the membranes were allowed to soak for 10 minutes, after which the pump was again turned on and the cleaning solution recirculated through the system for another 10 minutes. The cleaning solution was drained from the system and the membranes were rinsed with DI water.

A second batch concentration identical to the previous one was conducted to see if membrane performance was affected by successive batches.

5.0 RESULTS AND DISCUSSION

5.0 RESULTS AND DISCUSSION

5.1 Leachate Characteristics

The two leachate samples were obtained from the Burlington landfill site. The leachate samples contained combined flows from toe drains located at the east and west side of the site as well as a drain located at the transfer station.

Characterization of the two leachate samples collected for test work is given in Table 5.1. The first sample was collected on July 17, 1987 and the second sample was collected on September 17, 1987. On July 17, 1987 the weather was hot and dry and the flow through the manhole was 95 liters per minute (L/min) (36,000 US gal/day). On September 17, 1987, the flow of leachate was higher at 110 L/min apparently as a result of wet weather conditions. As can be seen from Table 5.1, the sample obtained during September 1987 is somewhat more dilute than the sample obtained in July 1987.

5.2 Microfiltration Experimental Results

5.2.1 Microfiltration Screening Test Results (Tests #1,2, and 3)

Significant differences were observed in permeate quality and flux with the different pretreatment methods used. Figure 5.1 shows the flux or permeate rates over the course of the testing. The highest flux rate was obtained with lime pretreatment, where the initial flux rate was 12.2 m3/m3/day (300 USgfd) but stabilized at 6.1 m3/m2/day

Table 5.1
Raw Leachate Characterization

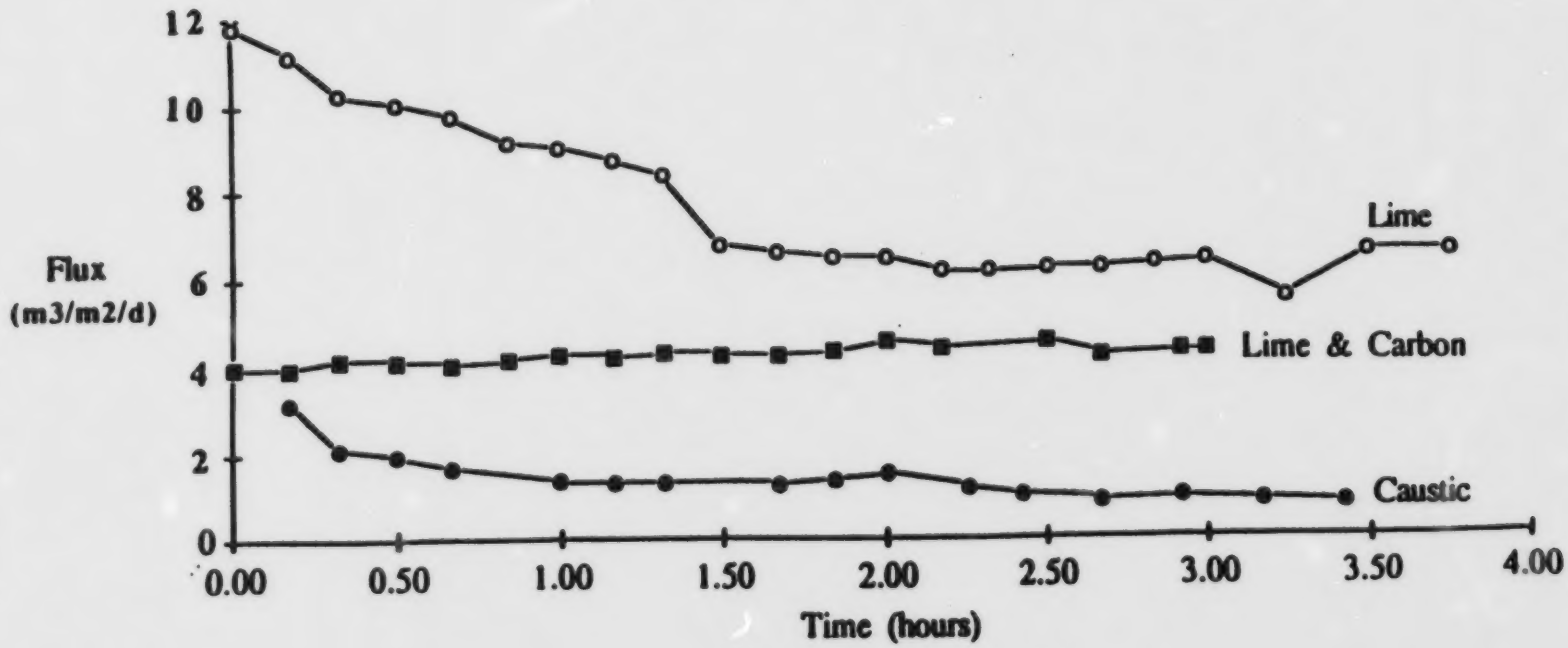
Parameter	Units	July 1987	Sept 1987
pH		6.8	6.6
Conductivity	(mmhos)	5.88	5.07
Turbidity	(NTU)	15.0	3.6
TSS	(mg/L)	290	430
TDS	(mg/L)	6,930	6,100
Fluoride	(mg/L)	na	na
Chloride	(mg/L)	200	670
Nitrite (as N)	(mg/L)	<0.2	<0.2
Bromide	(mg/L)	<0.8	<0.8
Nitrate (as N)	(mg/L)	<0.2	0.96
Phosphate (as P)	(mg/L)	<0.8	<0.8
Sulfate	(mg/L)	11	380
Alkalinity (as CaCO3)	(mg/L)	3,740	2,600
Calcium	(mg/L)	570	540
Magnesium	(mg/L)	380	240
Sodium	(mg/L)	740	430
Potassium	(mg/L)	310	240
Aluminum	(mg/L)	0.41	1.0
Barium	(mg/L)	1.1	0.063
Beryllium	(mg/L)	<0.0003	<0.01
Boron	(mg/L)	6.1	5.2
Cadmium	(mg/L)	<0.002	<0.01
Chromium	(mg/L)	0.046	0.15
Cobalt	(mg/L)	<0.01	<0.01
Copper	(mg/L)	<0.006	<0.01
Iron	(mg/L)	130	79
Lead	(mg/L)	<0.04	<0.4
Manganese	(mg/L)	7.6	7.1
Molybdenum	(mg/L)	<0.02	<0.1
Nickel	(mg/L)	0.055	0.15
Phosphorous	(mg/L)	1.6	4.7
Silicon	(mg/L)	17	12
Silver	(mg/L)	<0.01	<0.1
Strontium	(mg/L)	7.3	5.3
Thallium	(mg/L)	<0.02	<0.2
Titanium	(mg/L)	<0.01	0.91
Vanadium	(mg/L)	<0.02	<0.1
Zinc	(mg/L)	2.0	2.4
Zirconium	(mg/L)	<0.01	<0.1

Parameter	Units	July 1987	Sept 1987
BOD	(mg/L)	2,200	3,500
COD	(mg/L)	3,030	4,700
TOC	(mg/L)	1,900	1,650
TOX	(ug/L)	228	100
Volatiles			
Methylene chloride	(ug/L)	121	72
1,1-Dichloroethane	(ug/L)	91	4.1
Benzene	(ug/L)	1.5	7.1
Toluene	(ug/L)	57.3	79
Ethyl benzene	(ug/L)	11.2	4.2
0-Xylene/ m-Xylene	(ug/L)	33.5	na
p-Xylene	(ug/L)	19.6	na
Extractables			
Bis(2-ethylhexyl)phthalate	(mg/L)	0.6	0.35
Di-n-octyl phthalate	(mg/L)	0.34	< 0.1
Diethyl phthalate	(mg/L)	1.1	0.85
Phenol	(mg/L)	5.3	3.9

na - not available

Figure 5.1

Flux for Mic[illegible]ltration Tests 1, 2 and 3



(150 USgfd). A stable flux rate of 4.1 $m^3/m^2/day$ (100 USgfd) was obtained with the addition of lime and powdered activated carbon. The lowest flux rate of 0.78 $m^3/m^2/day$ (19 USgfd) was obtained with pretreatment precipitation using caustic.

The results of chemical analysis on raw leachate and microfiltration permeate from the first three MF experiments are shown in Table 5.2. As expected, total suspended solids (TSS) were virtually completely removed by the microfiltration process with all of the chemical precipitation methods while total dissolved solids (TDS) shows almost no reduction. Total Organic Carbon (TOC) levels were reduced slightly (10-11%) with use of caustic and lime and somewhat more (32%) with the combined lime plus carbon treatment. Total organic halogen (TOX) was reduced to a considerably higher degree than the rest of the organic carbon particularly when activated carbon was used in addition to the lime. Calcium was removed almost completely when caustic (NaOH) was used to adjust the pH but very little when lime ($Ca(OH)_2$) which contains additional calcium was used. Few metals were present in the raw leachate sample but iron was present at 130 mg/l. Iron was completely removed by microfiltration after treatment by all three precipitation methods used. Xylene and toluene were present in the raw feed and appear to have been completely removed in the microfiltration process. This reduction may be due to the organics being associated with solids which are rejected or may be the result of loss due to volatilization. Longer term testing with large samples volumes will be required to determine the actual rejection of these organics.

Table 5.2
Feed and Permeate Quality for Microfiltration Tests 1, 2 and 3

Parameter	Units	Raw Feed	Test 1		Test 2		Test 3	
			MF Permeate	Percent Rejected	MF Permeate	Percent Rejected	MF Permeate	Percent Rejected
pH		6.8	9.7	--	10	--	9.9	--
Conductivity	(mmhos)	5.88	6.05	-3%	4.06	31%	3.86	34%
Turbidity	(NTU)	15	0.96	94%	0.55	96%	0.1	99%
TSS	(mg/L)	290	6.5	98%	2.7	99%	1.5	99%
TDS	(mg/L)	6930	8530	-23%	5790	16%	4970	28%
TOX	(ug/L)	228	110	52%	31.4	86%	4.3	98%
TOC	(mg/L)	1900	1710	10%	1690	11%	1290	32%
Alkalinity	(mg/L)	3740	4160	-11%	2000	47%	1760	53%
Calcium	(mg/L)	570	5.7	99%	510	11%	450	21%
Magnesium	(mg/L)	380	200	47%	140	63%	110	71%
Iron	(mg/L)	130	0.029	>99%	<0.01	>99%	<0.01	>99%
Xylene	(mg/L)	0.11	<0.02	>99%	<0.02	>99%	<0.02	>99%
Toluene	(mg/L)	0.14	0.04	71%	0.02	86%	<0.01	>99%
Benzene	(mg/L)	<0.02	<0.02	--	<0.02	--	<0.02	--

Chemical Pretreatment
Test # 1 - Caustic to pH 10.
Test # 2 - Lime to pH 10.
Test # 3 - Lime to pH 10 and 20 g/L of powdered activated carbon.

5.2.2 Large Volume Microfiltration Test Results (Test 4 & 5)

Figure 5.2 shows the permeate flux over the course of the batch concentration for test #4. The initial flux was approximately 8.8 $m^3/m^2/day$ (215 USgfd) but stabilized at approximately 4.1 $m^3/m^2/day$ (100 USgfd) after three and one half hours of operation (17% volume reduction). The system was shut down over night and when restarted the flux was 4.9 $m^3/m^2/day$ (120 USgfd). It again stabilized near 4.1 $m^3/m^2/day$ (100 USgfd) at 15 hours elapsed running time. The temporary increase may have been due to an initial flushing off of material from the membrane surface at start up, which was re-established later on. A significant decrease in the flux is observed after 24 hours of operation corresponding to 80% volume reduction (concentration factor of 5). The concentration run was ended after 30 hours of operation at a volume reduction of 88% by which time flux had dropped to 0.86 $m^3/m^2/day$ (21 USgfd).

Analytical results of the MF pretreatment at the three sample points; feed, concentrate, and permeate are given in Table 5.3 and 5.4. The results show a significant reduction in turbidity, TSS and magnesium in the permeate, due to precipitation of metal hydroxides and suspended material after adjustment of the pH with lime, and followed by microfiltration. Little rejection of the conductivity and TDS was observed as expected since microfiltration membranes do not reject in the ionic range. There is a slight rejection of TOC which indicates that the majority of the organic matter is small enough to

Figure 5.2

Flux for Microfiltration Test 4

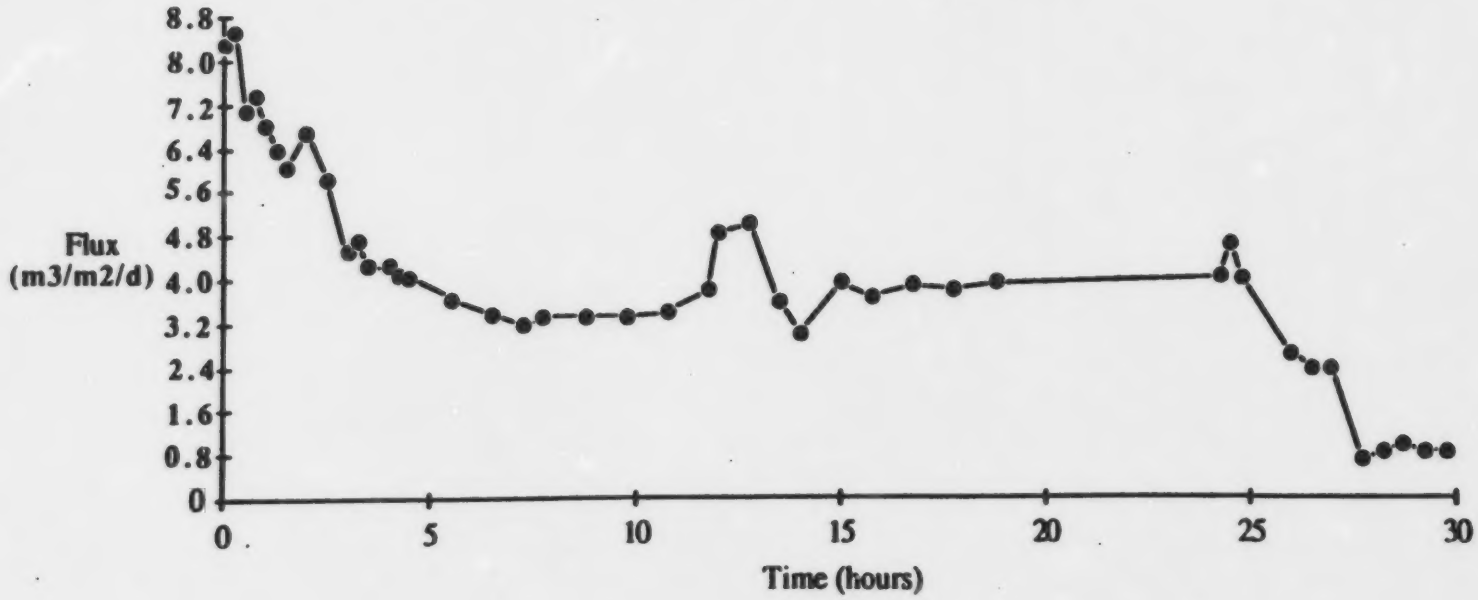


Table 5.3
Feed and Permeate Quality for Microfiltration Tests 4 and 5
Inorganic Analysis

Parameter	Units	Test 4			Test 5		
		Raw Feed	MF Permeate	% Rejection	Raw Feed	MF Permeate	% Rejection
pH		6.55	11.85	–	7.0	10.7	–
Conductivity	(mmhos)	5.1	6.9	-35%	4.1	4.8	-17%
Turbidity	(NTU)	3.6	0.5	86%	24	0.6	98%
TSS	(mg/L)	430	21	95%	200	60	70%
TDS	(mg/L)	6,100	6,680	-10%	na	na	–
Fluoride	(mg/L)	na	na	–	na	130	–
Chloride	(mg/L)	670	930	-39%	na	3600	–
Nitrite (as N)	(mg/L)	<0.2	<0.2	–	na	<0.20	–
Bromide	(mg/L)	<0.8	<0.8	–	na	<0.8	–
Nitrate (as N)	(mg/L)	0.96	1.0	-4%	na	1.0	–
Phosphate (as P)	(mg/L)	<0.8	<0.8	–	na	<0.8	–
Sulfate	(mg/L)	380	390	-3%	na	<1.0	–
Alkalinity (as CaCO3)	(mg/L)	2,600	2,800	-8%	na	240	–
Calcium	(mg/L)	540	1,100	-104%	400	22	95%
Magnesium	(mg/L)	240	1	>99%	340	140	59%
Sodium	(mg/L)	430	420	2%	560	2000	-257%
Potassium	(mg/L)	240	230	4%	250	260	-4%
Aluminum	(mg/L)	1	0.3	70%	0.75	<0.03	>96%
Barium	(mg/L)	0.063	0.071	-13%	0.75	0.003	>99%
Beryllium	(mg/L)	<0.01	<0.01	–	<0.005	<0.001	–
Boron	(mg/L)	5.2	4.1	21%	5	3.6	28%
Cadmium	(mg/L)	<0.01	<0.01	–	<0.01	<0.002	–
Chromium	(mg/L)	0.15	<0.1	>99%	0.075	0.012	84%
Cobalt	(mg/L)	<0.1	<0.1	–	<0.05	<0.01	–
Copper	(mg/L)	<0.1	<0.1	–	<0.05	0.019	–
Iron	(mg/L)	79	<0.2	>99%	75	0.094	>99%
Lead	(mg/L)	<0.4	<0.4	–	<0.2	<0.04	–
Manganese	(mg/L)	7.1	2.9	59%	4.5	0.007	>99%
Molybdenum	(mg/L)	<0.1	<0.1	–	<0.05	<0.01	–
Nickel	(mg/L)	0.15	<0.1	>33%	<0.05	0.074	–
Phosphorus	(mg/L)	4.7	2.6	45%	3.7	0.96	74%
Silicon	(mg/L)	12	1.1	91%	10	3.3	67%
Silver	(mg/L)	<0.1	<0.1	–	<0.05	<0.01	–
Strontium	(mg/L)	5.3	1.2	77%	5.9	0.18	97%
Thallium	(mg/L)	<0.2	<0.2	–	<0.25	<0.05	–
Titanium	(mg/L)	0.91	0.85	7%	<0.05	<0.01	–
Vanadium	(mg/L)	<0.1	<0.1	–	<0.05	<0.01	–
Zinc	(mg/L)	2.4	<0.1	>96%	2	0.019	99%
Zirconium	(mg/L)	<0.1	<0.1	–	<0.05	<0.01	–

na = not available

Chemical Pretreatment

Test # 4 - Lime to pH 10

Test # 5 - Lime to pH 10 & Soda Ash

Table 5.4
Feed and Permeate Quality for Microfiltration Tests 4 and 5
Organic Analysis

Parameter	Units	Test 4			Test 5		
		Raw Feed	MF Permeate	% Rejection	Raw Feed	MF Permeate	% Rejection
COD	(mg/L)	4,700	4,300	9%	na	na	-
BOD	(mg/L)	3,500	3,000	14%	na	na	-
TOC	(mg/L)	1,650	1,400	15%	na	na	-
TOX	(ug/L)	100	120	-20%	na	na	-
Methylene chloride	(ug/L)	72	150 *	-	na	na	-
trans-1,2-Dichloroethene	(ug/L)	4.1	<3.0	>27%	<1.0	<1.0	-
1,1-Dichloroethane	(ug/L)	60	<3.0	>95%	100	7.2	93%
1,2-Dichloroethane	(ug/L)	5.9	<3.0	>49%	25	2.7	89%
Benzene	(ug/L)	7.1	<3.0	>58%	59	5.7	90%
Toluene	(ug/L)	79	36	54%	550	320	42%
Ethyl benzene	(ug/L)	4.2	3.3	21%	79	1.5	98%
Tetrachloroethane	(ug/L)	8.1	<3.0	>63%	<1.0	<1.0	
Bis(2-ethylhexyl)phthalate	(mg/L)	0.35	0.37	-6%	na	2.4	-
Diethyl phthalate	(mg/L)	0.85	< 0.1	>88%	na	<2.0	-
Phenol	(mg/L)	3.9	1.1	72%	na	na	-

na = not avaliable

* - Possible Erroneous Result, Methylene Chloride is a common Laboratory Contaminant.

Chemical Pretreatment

Test # 4 - Lime to pH 10

Test # 5 - Lime to pH 10 & Soda Ash

pass through the MF membrane. The reduction in some organics, such as toluene, may be due to absorption on solids which were then rejected by the MF membrane.

The concentration of calcium in the MF permeate in this experiment was higher than previous tests and indicates addition of excess lime to the leachate. To prevent over addition of lime in subsequent experiments, the amount of time for the lime to react was increased and a lime slurry was used to allow the lime to react more quickly. The levels of calcium in the MF permeate still represented a potential problem for the RO treatment step. In subsequent experiments, soda ash was used along with the lime to improve the removal of calcium.

Analytical results presented in Table 5.4 includes only the organic parameters which were present in the feed at detectable levels. Complet lytical results for organic compounds are given in Appendix B.

Analysis of volatile organics reveal a general trend of removal of these compounds in the MF permeate. This could be due to volatilization or adsorption onto the solid particles and rejection of the larger particulate. The concentration of methylene chloride in the permeate is high and may be an anomalous result due to laboratory contamination since methylene chloride is a common laboratory contaminant. The extractable organics were also removed to some degree in the microfiltration pretreatment.

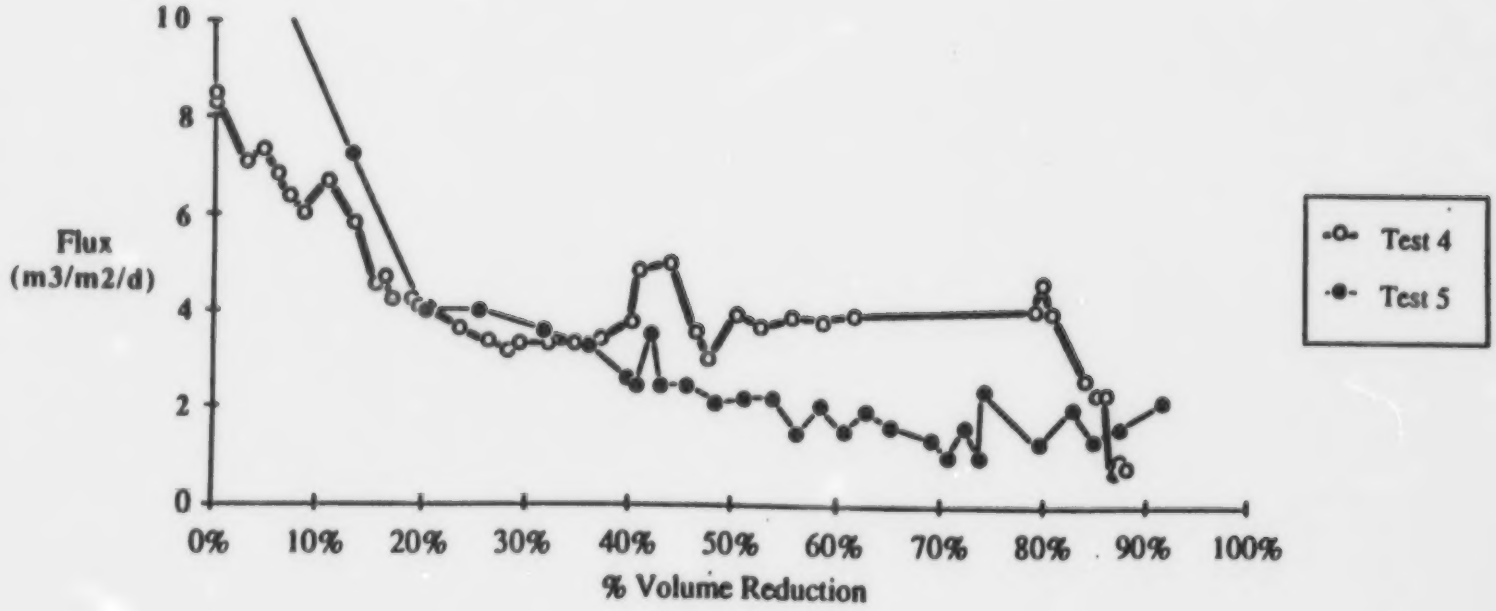
The MF batch concentration test indicates that a reasonable MF flux rate, 4.1 m3/m2/day (100 USgfd), can be obtained at 80% volume reduction. The test also confirms the results of previous testing which show a significant decrease in magnesium, aluminum, iron, zinc and TSS.

The fifth and final microfiltration test was conducted using lime and soda ash to precipitate the metals and calcium. Figure 5.3 shows the permeate flux for tests #4 and 5 against the percent volume reduction. The initial flux was 21.5 m3/m2/day (526 USgfd) and stabilized to approximately 2.0 m3/m2/day (50 USgfd) at a 50% volume reduction. The testing took place over a 29 hour period and the volume of feed was reduced from an initial volume of 230 L of raw feed to 20 L, achieving a 92% volume reduction. The major drop in flux up to a at 20% volume reduction (a concentration factor of 1.25), this corresponded to two hours of operation.

Considerable variation in the flux rate has been observed with different precipitation methods. The addition of excess lime in Test four may have resulted in a large floc formation and better removal by the MF membrane. The addition of soda ash in the test five may have resulted in a different floc formation, possibly more gelatinous which affected the membrane performance providing a somewhat lower flux.

Figure 5.3

Flux for Microfiltration Tests 4 and 5



The performance of microfiltration membranes are affected by the chemicals used and by the specific chemistry of the membrane polymer and membrane additives used. Certain additives can repel particular compounds which may be causing fouling of the membrane and allow for much higher and more stable flux rates to be obtained. The results obtained here are for one type of microfiltration membrane chemistry and optimization of the particular membrane chemistry may yield higher and more stable flux for this particular application. Optimization of the dosage of the precipitation chemicals will also likely result in improved membrane performance.

Analytical results of gross parameters of the raw feed, and MF permeate are given in Tables 5.3 and 5.4, along with results from previous testing. As can be seen, in the results from Test 5, addition of lime and soda ash has resulted in a very slight increase in conductivity as expected since microfiltration membranes do not reject in the ionic range. The turbidity has decreased by 98%. The measured total suspended solids in the MF permeate was 60 mg/L. This is likely an erroneous result due to precipitation of some dissolved components after microfiltration.

A substantial reduction in the calcium and magnesium content was achieved through the use of lime with soda ash, but an increase in sodium ion concentration occurs. This is a significant improvement from the previous test. Since sodium ions, or their complexes, do not foul the membrane, an increase in concentration is not a major concern.

Magnesium and silicon were not removed as well in the fifth test compared to the fourth test, and may be a result of the higher pH in the first test. Improved removal was observed for aluminum, barium, boron, manganese, phosphorus, and strontium. No difference in removal of potassium, beryllium, cadmium, cobalt, iron, lead, molybdenum, silver, thallium, vanadium, and zinc was observed between the two tests.

Good removal of the volatile component was achieved with both microfiltration methods. A higher feed concentration of toluene in Test five is due to spiking. Comparable removal of toluene was achieved with both tests, Test 4-54%, Test 5-42%. Improved removal of ethyl benzene is observed in Test five. Results from the two tests confirm that pretreatment by chemical precipitation followed by microfiltration provide excellent removal at varying feed concentration for both inorganic and organic components of landfill leachate.

5.3 Reverse Osmosis Experimental Results

5.3.1 Flat Sheet RO Screening Test Results

The RO Screening Test provided information on the permeate quality and flux rates possible with different membranes. Evaluation of the four RO membranes was based on the following four criteria:

1) Flux rates obtainable using leachate treated by microfiltration as feed.

2) Anticipated lifetime and maintenance required for the membrane indicated by loss in flux.

3) Permeate quality.

4) Availability and cost of the RO spiral module.

The flux results of the RO screening test conducted using permeate from the fourth microfiltration experiment are shown in Figure 5.4. After an initial stabilization period, the flux of the membranes relative to each other remained fairly constant. The average flux rates of the membranes during the stability test were:

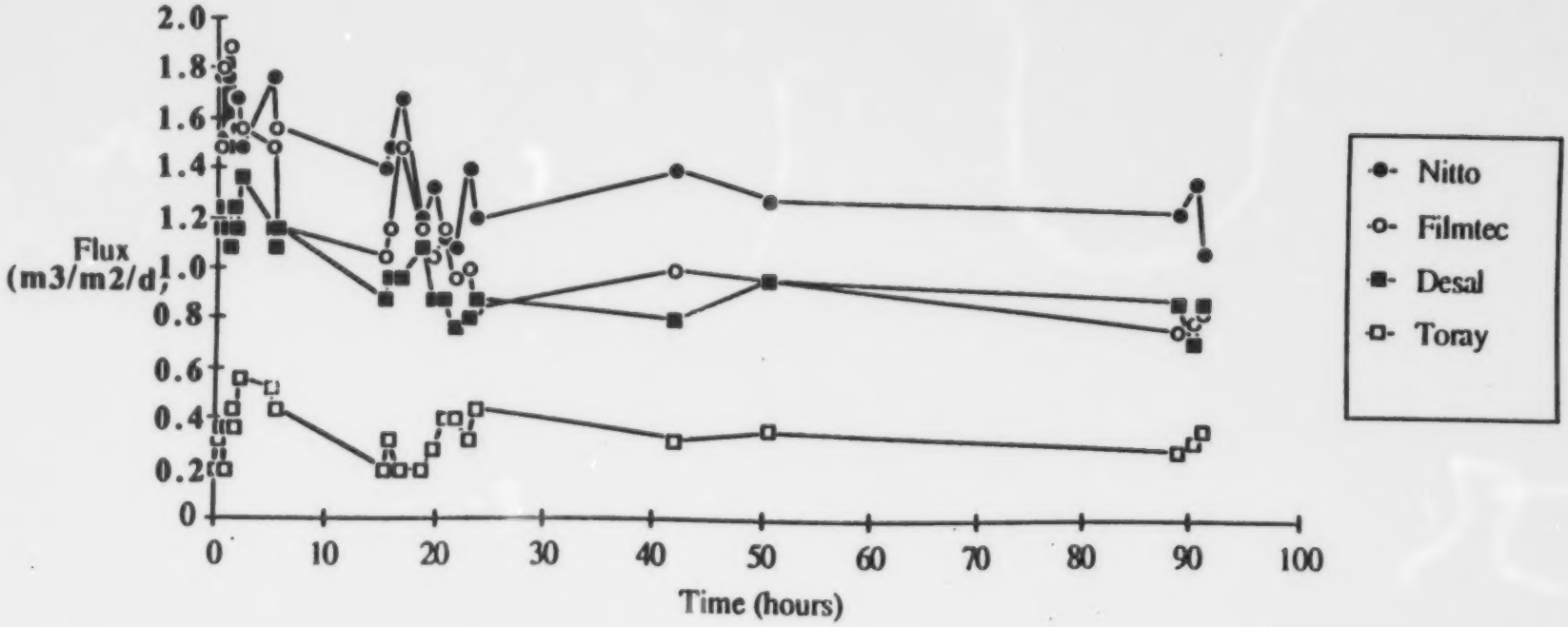
MEMBRANE	FLUX ($m^3/m^2/day$)
Nitto:	1.5
Filmtec:	1.3
Desal:	1.0
Toray:	0.4

The results of the salt water flux tests provide an indication of the loss in flux which results from exposure to leachate feed for the different membranes tested. The results of the saltwater flux tests conducted before and after stability testing are as follows:

Membrane	Salt Flux Before Testing ($m^3/m^2/day$)	Salt Flux After Testing ($m^3/m^2/day$)	Loss In Flux
Nitto	2.0	1.7	0.3
Filmtec	2.6	1.4	1.2
Desal	1.9	1.2	0.7
Toray	0.4	0.4	0.0

Figure 5.4

Flux for Flat Sheet Reverse Osmosis Tests



The Toray membrane had the lowest flux but showed no change in the flux after testing. The Nitto membrane showed a slight decrease in flux rate, and the Desal and Filmtec membranes both showed considerable decrease in flux as a result of exposure to the pretreated leachate.

Table 5.5 presents the analytical results from the testing. All four membranes provide a high quality permeate. The Filmtec and Toray provide the best quality permeate, the Desal permeate was not quite as clean, and permeate from the Nitto membrane contained the highest level of contamination.

Both Filmtec and Toray membranes provided high quality permeate, but based on the higher flux, the Filmtec membrane was selected for further testing. The Nitto membrane also performed well and was chosen as an additional membrane for further testing.

5.3.2 Spiral Reverse Osmosis Membrane Testing Results

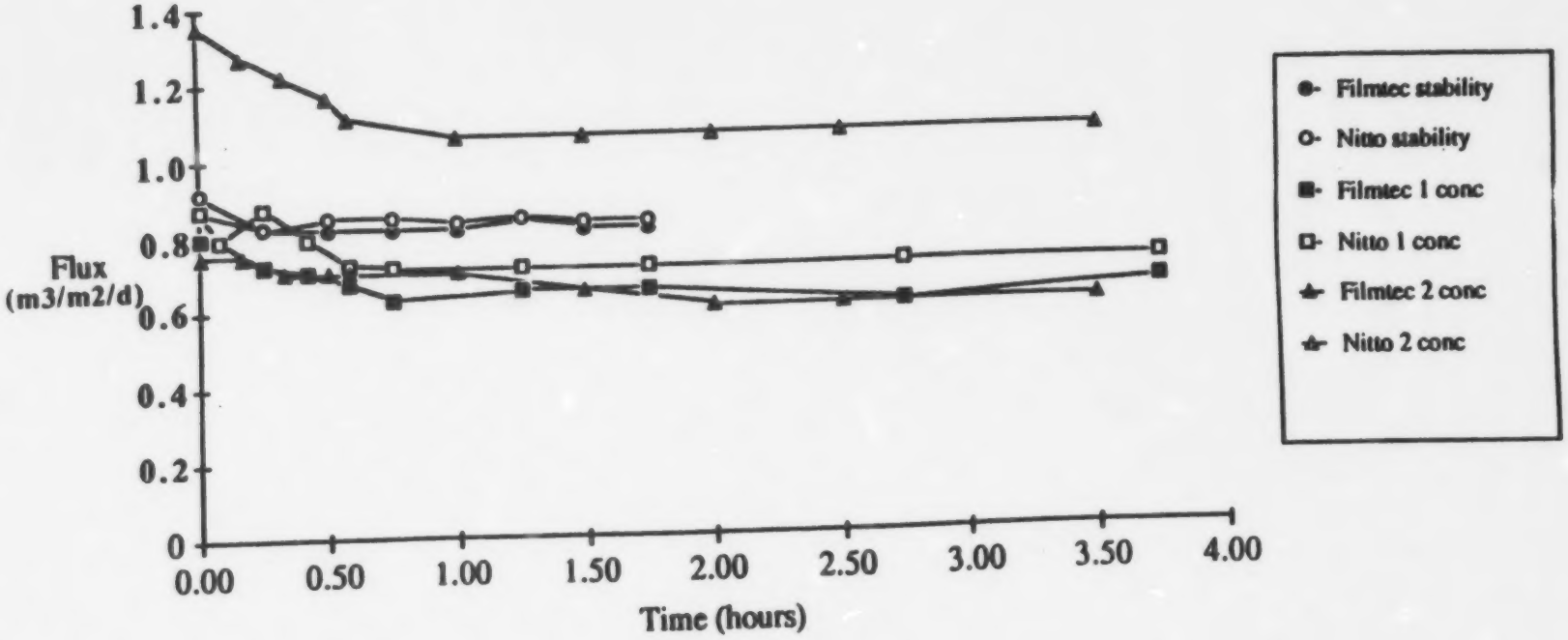
The stability and concentration test flux for the spiral RO testing are shown in Figure 5.5. As can be seen, the flux for the Filmtec and Nitto spiral membranes during the stability test were virtually the same at 0.86 m3/m2/day (21 USgal/sq.ft./day). In the first concentration test, the flux for both membranes decreased. Filmtec permeate flux stabilized to approximately 0.65 m3/m2/day (16 USgal/sq.ft./day), while Nitto permeate flux stabilized at Figure 5.5

Table 5.5
Feed and Permeate Quality for Flat Sheet Reverse Osmosis Testing

Parameter	Units	Feed	RO Conc	Filmtec		Nitto		Toray		Desal	
				RO Perm.	% Rej.	RO Perm.	% Rej.	RO Perm.	% Rej.	RO Perm.	% Rej.
pH		11.85	5.35	4.6		5.5		6.7		5.9	
Conductivity	(mmhos)	6.86	9.37	0.20	97%	0.65	91%	0.20	97%	0.26	96%
Turbidity	(NTU)	0.5	1.0	0.3	40%	0.4	20%	0.2	60%	0.5	0%
TSS	(mg/L)	21	69	<1.0	>99%	<1.0	>99%	<1.0	>99%	<1.0	>99%
TDS	(mg/L)	6680	7500	140	98%	380	94%	120	98%	120	98%
TOX	(ug/L)	120	200	27	78%	14	88%	3	98%	8.9	93%
TOC	(mg/L)	1400	2000	61	96%	98	93%	46	97%	57	96%
Calcium	(mg/L)	540	1700	3.3	99%	28	95%	1.7	100%	11	98%
Magnesium	(mg/L)	1	1.6	<0.05	>99%	<0.05	>99%	<0.05	>99%	<0.05	>99%
Xylene	(mg/L)	<0.01	<0.01	<0.01	>99%	<0.01	>99%	<0.01	>99%	<0.01	>99%
Toluene	(mg/L)	0.03	<0.01	<0.01	>99%	<0.01	>99%	<0.01	>99%	<0.01	>99%
Benzene	(mg/L)	<0.01	<0.01	<0.01	>99%	<0.01	>99%	<0.01	>99%	<0.01	>99%

Figure 5.5

Flux vs Time for Spiral Reverse Osmosis Tests



approximately 0.73 m3/m2/day (18 USgal/sq.ft./day). After washing the membranes, a second concentration test was performed and Filmtec's permeate flux stabilized at 0.61 m3/m2/day (15 USgal/sq.ft./day), and Nitto's permeate flux stabilized at 1.06 m3/m2/day (26 USgal/sq.ft./day).

The rejection of ions, based on conductivity readings, during the stability and concentration test runs are shown in Table 5.6. The Filmtec membrane consistently rejected 99% of the conductivity. In the initial stability test the Nitto membrane's final rejection was 93%. After the first concentration test the ionic rejection was 90% and after the second concentration test the ionic rejection decreased to 84%. The Nitto membrane's ability to reject ions decreased with each test, indicating that either the membrane degraded significantly with exposure to the pretreated leachate or a leak developed around some mechanical seal in the membrane module.

Figure 5.6 shows the flux during the concentration tests against the volume reduction. The Filmtec permeate flux remained virtually the same for the two concentration tests at approximately 0.65 m3/m2/day (16 USgal/sq.ft./day) in the first concentration test, and 0.73 m3/m2/day (18 USgal/sq.ft./day) in the second concentration test at 50% volume reduction. The Nitto membrane flux rate was 0.73 m3/2/day (18 USgal/sq.ft./day), and 1.14 m3/m2/day (28 USgal/sq.ft./day) in the first and second concentration tests at 50%. There was very little decrease in flux during concentration for both

Table 5.6
Conductivity Rejection For Spiral RO Testing
Pretreated Leachate Sample

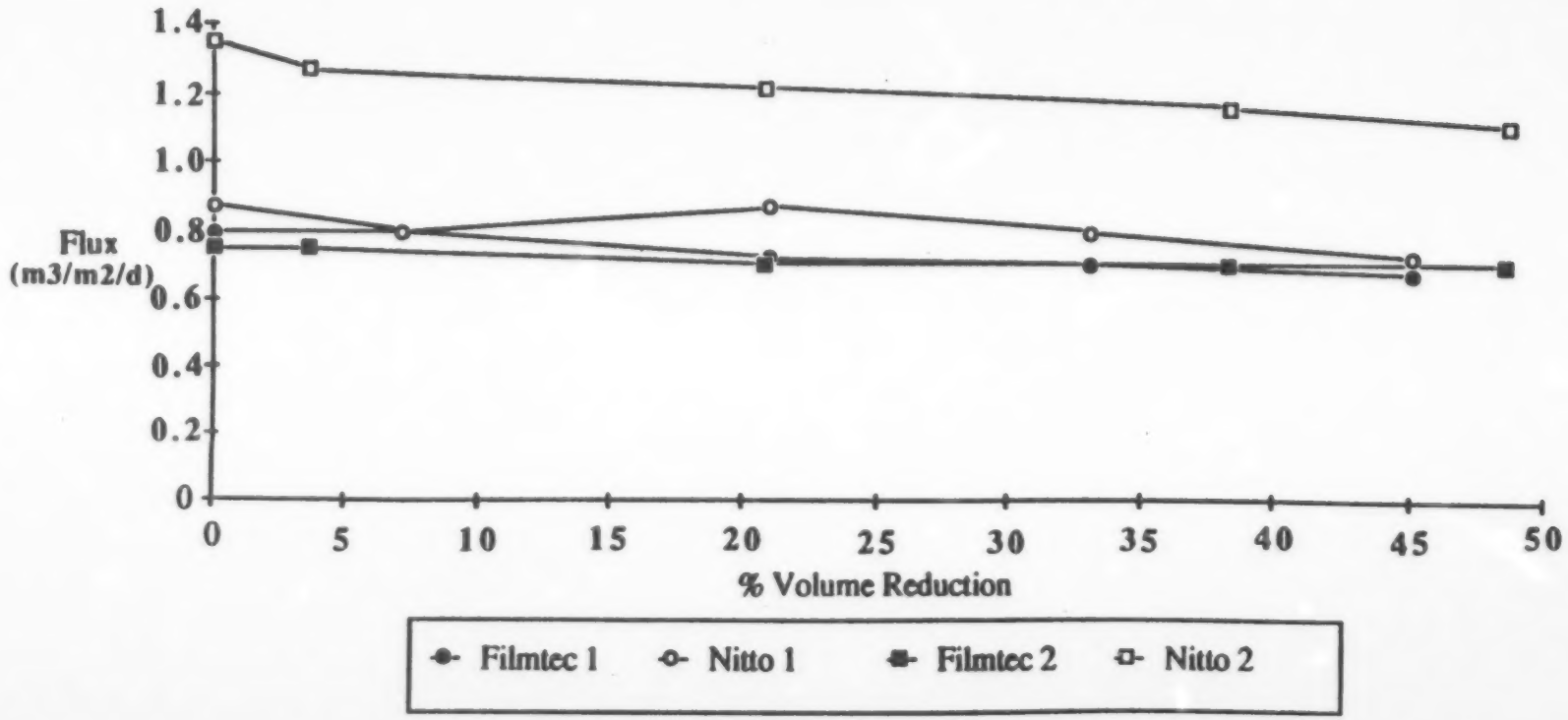
Test	Nitto	Filmtec
	% Rejection	% Rejection
Stability Test	93%	99%
1st Concentration	90%	99%
2nd Concentration	84%	99%

Table 5.7
Conductivity Rejection and Flux For Spiral RO Testing
Standard Saltwater Test

Test	Nitto		Filmtec	
	Flux (m3/m2/d)	% Rejection	Flux (m3/m2/d)	% Rejection
Initial	0.79	65%	0.67	76%
After Stability	0.62	94%	0.62	99%
After 1st Concent	0.62	94%	0.59	99%
After Wash	1.13	92%	0.53	99%
After 2nd Conc	0.86	90%	0.55	99%

Figure 5.6

Flux vs Volume Reduction for Spiral Reverse Osmosis Concentration Tests



membranes suggesting that it may be possible to concentrate the feed to a higher volume recovery without a significant decrease in flux.

Saltwater flux tests were performed before and after each stability or concentration test to determine whether the membranes had changed due to exposure to the pretreated leachate. A summary of the results is given in Table 5.7. In the initial set of saltwater tests, flux was reasonable for both membranes but rejection was very poor. After the stability test the flux was virtually the same but the rejections improved considerably. Nitto and Filmtec both had a flux of 0.62 $m^3/m^2/day$ (15 USgal/sq.ft./day) and Filmtec's rejection was 99%, while Nitto's rejection was 94%.

Washing the membranes improved Filmtec's flux slightly and significantly improved Nitto's fluxrate from 0.61 $m^3/m^2/day$ (15 USgal/sq.ft./day) to 1.14 $m^3/m^2/day$ (28 USgal/sq.ft./day). The corresponding ionic rejection went from 94% to 92%, indicating a slight decrease in Nitto's ability to reject ions after washing. Both the flux and ionic rejection obtained from the Nitto membrane decreased after the second concentration test from 1.14 $m^3/m^2/day$ (28 USgal/sq.ft./day) to 0.86 $m^3/m^2/day$ (21 USgal/sq.ft./day) and 92% to 90%. The Filmtec membrane's ability to reject ions remained stable after the initial stability test.

Due to the superior quality of the Filmtec permeate and the

stable flux rates, more complete chemical analysis of the permeate and concentrate were conducted. Table 5.8 presents results of the analysis of permeate from each of the three tests. The removal of conductivity, TOC and TOX remained high throughout the 3 tests. Conductivity removal was 97 to 98%, TOC was 97 to 99% and TOX removal remained at 99% for the series of tests.

Table 5.9 and 5.10 presents the inorganic and organic results of the raw feed, RO feed, and Filmtec permeate for the 2nd concentration run. Organic analytical results presented in the table include only the parameters which were presen ne feed at detectable levels. Complete analytical results for organic compounds are given in Appendix B. Excellent removal is observed for the inorganic contaminants.

Measurements of the organic content including TOC, BOD and TOX showed virtually complete rejection (98%) of organic compounds. All inorganic compounds which were present above the minimum detection limit with the exception of boron showed rejection of at least 97%. Very few heav s were present in the original feed and those that were pres were removed in the precipitation microfiltration pretreatment. The RO rejected a very high percentage (98%) of the dissolved solids as measured by conductivity from the RO feed.

The feed to the RO system had been spiked with pentachlorophenol (PCP) and toluene. The feed to the RO contained 430

Table 5.8
Feed and Permeate Quality for Spiral Reverse Osmosis Membrane Testing
Filmtec FT-30

Parameter	Units	RO Feed	RO Concentrate (2nd Conc.)	Stability Test		1st Conc. Test		2nd Conc. Test	
				RO Permeate	% Rejected	RO Permeate	% Rejected	RO Permeate	% Rejected
pH		6.1	6.18	5.5	--	5.08	--	5.22	--
Conductivity	(mmhos)	7.61	10.84	0.13	98%	0.21	97%	0.17	98%
Turbidity	(NTU)	6	2	0.2	97%	0.3	95%	0.8	87%
TSS	(mg/L)	90	3	na	--	na	--	na	--
TDS	(mg/L)	7500	5300	na	--	na	--	na	--
TOC	(mg/L)	1500	2400	31	98%	45	97%	15	99%
TOX	(ug/L)	200	210	1.5	99%	2.2	99%	1.9	99%

Note: Percent Rejections are based on Feed and Permeate Concentrations.

Table 5.9
Feed and Permeate Quality for Spiral RO Membrane Testing,
Second Concentration Run, Inorganic Compounds

Parameter	Units	Target	Raw Feed	Spiked RO Feed	Filmtec Permeate	% Rejection
pH			6.6	6.1	5.2	--
Conductivity	(mmhos)		5.07	7.6	0.17	98%
Turbidity	(NTU)		3.6	6	0.8	87%
TSS	(mg/L)		430	90	na	--
TDS	(mg/L)		6100	na	na	--
Fluoride	(mg/L)	<2.0	na	130	3.8	97%
Chloride	(mg/L)		670	3600	36	99%
Nitrite (as N)	(mg/L)		<0.2	<0.20	<0.20	-
Bromide	(mg/L)		<0.8	<0.8	<0.80	-
Nitrate (as N)	(mg/L)		0.96	1.0	<0.20	>80%
Phosphate (as P)	(mg/L)		<0.8	<0.8	<0.80	-
Sulfate	(mg/L)		380	<1.0	<1.0	-
Alkalinity (as CaCO3)	(mg/L)		2600	240	na	-
Calcium	(mg/L)		400	22	0.076	>99%
Magnesium	(mg/L)		340	140	0.38	>99%
Sodium	(mg/L)		560	2000	40	98%
Potassium	(mg/L)		250	260	8.2	97%
Aluminum	(mg/L)	<1.0	0.75	<0.03	<0.03	-
Barium	(mg/L)	<0.1	0.75	0.003	<0.001	>66%
Beryllium	(mg/L)		<0.005	<0.001	<0.001	-
Boron	(mg/L)		5	3.6	0.83	77%
Cadmium	(mg/L)	<0.1	<0.01	<0.002	<0.002	-
Chromium	(mg/L)	<1.0	0.075	0.012	<0.01	>16%
Cobalt	(mg/L)		<0.05	<0.01	<0.01	-
Copper	(mg/L)	<1.0	<0.05	0.019	<0.01	>47%
Iron	(mg/L)	<1.0	75	0.094	<0.01	>89%
Lead	(mg/L)	<1.0	<0.2	<0.04	<0.04	-
Manganese	(mg/L)	<1.0	4.5	0.007	<0.005	>28%
Molybdenum	(mg/L)		<0.05		<0.01	-
Nickel	(mg/L)	<1.0	<0.05		<0.01	>86%
Phosphorus	(mg/L)	<1.0	3.7		<0.1	>89%
Silicon	(mg/L)		10	3.3	<0.05	>98%
Silver	(mg/L)		<0.05	<0.01	<0.01	-
Strontium	(mg/L)		5.9	0.18	<0.001	>99%
Thallium	(mg/L)		<0.25	<0.05	<0.05	-
Titanium	(mg/L)		<0.05	<0.01	<0.01	-
Vanadium	(mg/L)		<0.05	<0.01	<0.01	-
Zinc	(mg/L)	<1.0	2	0.019	<0.01	>47%
Zirconium	(mg/L)		<0.05	<0.01	<0.01	-

Target Values are Storm Sewer restrictions for the Regional Municipality of Halton

Table 5.10
Feed and Permeate Quality for Spiral RO Membrane Testing,
Second Concentration Run, Organic Compounds

Parameter	Units	Target	Raw Feed	Spiked RO Feed	Filmtec Permeate	% Rejection
COD	(mg/L)		4,700	5,900	na	-
BOD	(mg/L)	<15	3,500	4,900	35	99%
TOC	(mg/L)		1,650	1,500	15	99%
TOX	(ug/L)		100	200	1.9	99%
Methylene chloride	(ug/L)		na	na	na	-
trans-1,2-Dichloroethene	(ug/L)		<1.0	<1.0	<1.0	-
1,1-Dichloroethane	(ug/L)		100	7.2	<1.0	>86%
1,2-Dichloroethane	(ug/L)		25	2.7	<1.0	>63%
Benzene	(ug/L)		59	5.7	110	-
Toluene	(ug/L)		550	320	100	69%
Ethyl benzene	(ug/L)		79	1.5	140	-
Tetrachloroethane	(ug/L)		<1.0	<1.0	<1.0	-
Bis(2-ethylhexyl)phthalate	(mg/L)		0.35	2.4	<1.0	>58%
Diethyl phthalate	(mg/L)		<2.0	<2.0	<2.0	-
Phenol	(mg/L)	<0.02**	3.9	430	30	93%

na = not avaliable

** - Phenolic compounds

mg/L of phenol and 320 ug/L of toluene. The permeate contained 30 mg/L of phenol and 100 ug/L of toluene demonstrating 93% rejection of phenol and 69% rejection of toluene.

The reverse osmosis experiments demonstrated the feasibility of RO for the concentration of residual organics and dissolved solids present in the permeate from a microfiltration process. The flux for the Filmtec membrane was stable through the duration of the testing. Rejection of organics as measured by the general parameters of TOC, BOD and TOX was consistently greater than 99%. Rejection of volatile organics such as toluene were significant but somewhat lower (69%).

6.0 ECONOMIC ASSESSMENT

6.0 ECONOMIC ASSESSMENT

6.1 Design Basis

Cost estimates have been prepared for a leachate treatment process consisting of addition of lime and soda ash in a mix tank, microfiltration to remove 85% of the water, plate and frame filter for dewatering the MF concentrate and reverse osmosis treatment to allow for 50% of the volumetric flow of the MF permeate to be discharged, while the remaining 50% is recycled back to the landfill site. In this process, the bulk of the metals and less soluble organics will be removed in the microfilter and will be concentrated in the solids from filter press. This material may be solidified and disposed of at the landfill site. The soluble organics which pass through the MF will be concentrated in the reverse osmosis process and recycled to the landfill site where biological activity will eventually breakdown these organics. Clean water from the RO process can be discharged to the sanitary or storm sewer or to a surface water course. A flow schematic for the process is shown in Figure 3.3.

The flow of leachate from the Burlington landfill site when samples were collected were 136 m^3/day and 160 m^3/day. Cost estimates have been prepared for capacities of 56.8, 113.5, and 170 m^3/day (15,000, 30,000, and 45,000 USgal/day). Equipment costs are based on a manufacturers selling price for packaged skid-mounted system components. Design specifications for the MF and RO processes were obtained from experimental data generated in this work. Total

installed costs for the process equipment were developed using the single factor method (Woods, 1980) to estimate the other direct and indirect costs of equipment. The installed costs include all costs associated with the facilities including foundations, instruments, piping, insulation, buildings, and services, as well as construction and field expenses, engineering and contractors fees. A factor of 2.1 times the equipment cost was used to estimate the total capital cost of the installation. The single factor of 2.1 was selected since the equipment costs include skid mounted prepiped equipment which required less on site installation than standard equipment.

Operating costs, including precipitation chemicals, replacement membranes, power consumption, labour, and contingencies, were calculated. Details of the design specifications for the system and assumptions made in the cost analysis are presented in Appendix C.

6.2 Treatment Process Costs

Table 6.1 shows the equipment costs, estimated installation costs, and total capital costs for the treatment process at three design capacities. The equipment costs show that there is some economy of scale for the larger capacity systems. The capital cost for the 56.8 m^3/day process is $261,832, while the cost for the 113.5 m^3/day process is $521,762, two times the cost for three times the capacity.

TABLE 6.1

EQUIPMENT COSTS AND TOTAL CAPITAL COSTS FOR LEACHATE TREATMENT PROCESS

Capacity (liters/day)	56,775	113,550	170,325
Capacity (USGFD/day)	15,000	30,000	45,000
Chemical Reaction System	$15,000	$17,000	$19,000
MF System	$46,013	$74,800	$95,200
Filter Press	$27,500	$43,152	$56,164
RO System	$36,169	$56,525	$78,094
Total Equipment Costs	$124,682	$191,477	$248,458
Installation Costs	$137,150	$210,625	$273,304
TOTAL CAPITAL COST	$261,832	$402,102	$521,762

Table 6.2 shows the operating costs for the process at the three design capacities. Costs for chemicals and labour used in these operating costs are presented in Appendix "C".

Table 6.3 shows the total costs for the leachate treatment process at the three selected design capacities. The total capital costs are amortized over 10 years at 11% interest. The total costs include the amortized capital costs (equipment and installation) and the operating costs for the process. The cost per m3 processed as shown in Figure 6.1 are $4.24, $3.62, and $3.32 for the 56.8 m3/day, 113.5 m3/day, and 170 m3/day process respectively.

These costs are somewhat higher than those suggested by Harrington et. al (1986) for alternative treatment processes of land irrigation, activated sludge and extended aeration with costs of $0.36/m3, $2.95/m3 and $0.93/m3. These alternative processes, however, have a number of shortcomings which make them unsuitable for leachate treatment at many landfill sites.

As discussed earlier, land irrigation is inappropriate at many locations because of contamination of soil by metals and refractory organics and heavy hydraulic loading on the site. The biological treatment options vary in cost considerably and both suffer from potential drawbacks of:

TABLE 6.2

OPERATING COSTS
FOR LEACHATE TREATMENT PROCESS

Capacity (liters/day)	56,775	113,550	170,325
Capacity (USGFD/day)	15,000	30,000	45,000
Precipitation Chemicals			
Lime at $0.074/kg	$4,600	$9,201	$13,801
Soda Ash at $0.23/kg	$7,149	$14,299	$21,448
MF Membrane Replacement Membrane Life Time of 2 years	$11,333	$22,667	$34,000
RO Membrane Replacement Membrane Life Time of 1.5 years	$4,167	$8,333	$12,500
MF System Power HP x 0.7457 x 24 x 365 x $0.0135 /KW	$900	$1,799	$2,699
RO System Power HP x 0.7457 x 24 x 365 x $0.0135 /KW	$2,205	$4,409	$6,614
Labour 1 / 1.5 / 1.75 hr. /day at $25/hr	$9,125	$13,688	$15,969
Contingencies	$3,948	$7,440	$10,703
YEARLY OPERATING COSTS	$43,427	$81,835	$117,734

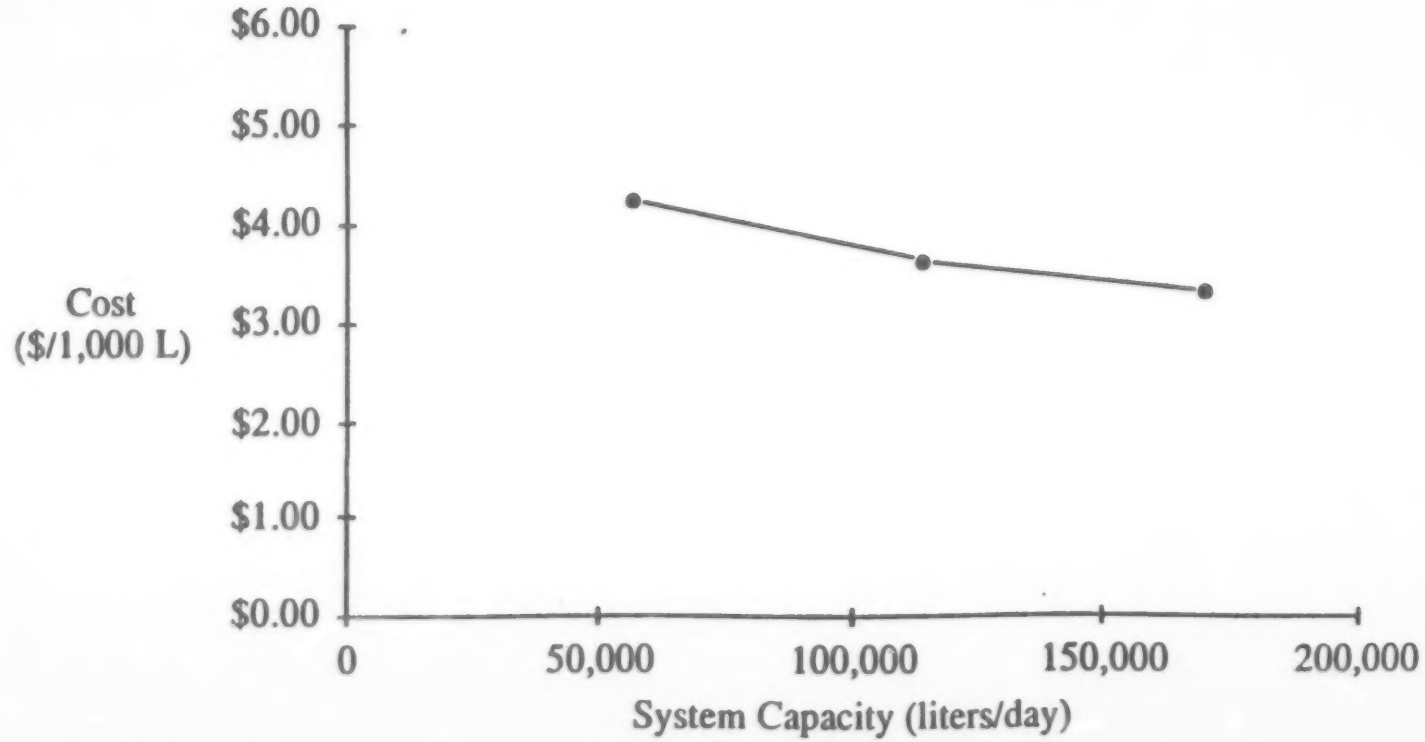
TABLE 6.3

AMORTIZED CAPITAL COSTS AND OPEATING COSTS FOR LEACHATE TREATMENT PROCESS

Capacity (liters/day)	56,775	113,550	170,325
Capacity (USGFD/day)	15,000	30,000	45,000
CAPITAL COSTS OF EQUIPMENT	$261,832	$402,102	$521,762
AMORTIZED CAPITAL COST Over 10 yr, at 11 %	$44,512	$68,357	$88,700
OPERATING COSTS	$43,427	$81,835	$117,734
TOTAL YEARLY COST	$87,938	$150,192	$206,434
COST PER 1,000 USGAL PROCESSED	$16.06	$13.72	$12.57
COST PER 1,000 LITERS PROCESSED	$4.24	$3.62	$3.32

FIGURE 6.1

COST PER 1,000 LITERS PROCESSED



1) inhibition due to toxic contaminants,

2) poor settling characteristics and product quality as a result of fluctuations in feed composition and nutrient levels,

3) carry over of metals and refractory organics and,

4) sludge disposal problems as a result of heavy metal contamination.

Alternative processes appear less expensive than the proposed precipitation microfiltration and reverse osmosis process but do not offer the same level of treatment and process reliability.

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7.0 REFERENCES

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APPENDIX A

ANALYTICAL METHODOLOGY

A.1 **Volatile Analysis - Halogenated/Non-Halogenated** (EPA 624)

An Envirochem Series 810 volatile analyzer was used for the analysis of all the samples and standards. 50 ng each of d_8-toluene, d_5-chlorobenzene, bromofluorobenzene, and d_4-dichloroethane were added as surrogate standards to all samples prior to analysis.

Standards were injected into 5.0 mL blank water and processed as a normal sample.

In addition, a system blank was analysed to establish any extraneous contribution of volatile organics.

5 mL sample was loaded into the purge vessel and processed using the following instrumental conditions:

Sparge: Helium 30 mL/min for 10 min.

Temperatures:

Trap #1 (Wide Bore)

- cool 50°C
- heat 250°C

Trap #2 (Narrow Bore)

- cool 50°C
- heat 250°C

Transfer line -250°C

G.C. Carrier Flow 3 mL/min.

The Hewlett-Packard mass selective detector (MSD) was used for all analyses. The gas chromatographic conditions are listed below:

Column:	30 M DB5 x 0.3 mm ID
Temp. Prog:	-45oC for 2 min.
	-45oC to 120oC at 10oC/min.
	120oC to 200oC at 20oC/min.
Injector:	Direct
Injection Temp:	150oC

The mass spectrometer conditions used in the analyses are listed below:

Electron Impace mode, scanning 45-300 AMU each second	
Electron energy	70 ev
Emission voltage	1300 ev
Emission Current	1.5 A

The U.S. EPA standard mixture was prepared by Radian Corporation. The GC/MS was calibrated with PFTBA (FC-43).

Quantification was performed using the external standard method, as detailed in the Federal Register (1984) on peak areas from reconstructed ion plots for the quantification ions listed in the EPA Federal Register. Assurance of correct identification was performed using the secondary ions and in the case of higher level determinations, using the full scan spectra.

A.2 **Extraction of Base/Neutral/Acid Extractables** (EPA 625)

The volume of the sample was measured in a 1 liter graduated cylinder and poured into a 2 liters separatory funnel. 10 milliliters (ml) of methylene chloride was used to rinse the cylinder and this was transferred into the funnel together with an additional 100 mL of methylene chloride. The pH of the aqueous portion was adjusted to 12 with 6N KOH and it was spiked with deuterated surrogate standards $^{2}H_{10}$ anthracene, $^{2}H_{12}$ benzo(a)pyrene, and $^{2}H_{3}$ dichlorophenol to monitor recovery in the procedure.

The sample was shaken vigorously for 1 minute and when the phases had separated the methylene chloride extracted was drained through a 3.8 cm anhydrous Na_2SO_4 column in an Allihn filter. The aqueous portion was re-extracted twice as above with 75 mL of methylene chloride. After the third extraction, the pH of the sample was adjusted to approximately pH 2 with 6N H_2SO_4 and was extracted as above 3 times with 75 mL methylene chloride. Twenty milliliters of methylene chloride was used to wash the walls of the Allihn filter and suction was applied to recover all traces of the extract. The extract was then rotary evaporated to approximately two milliliters and quantitatively transferred to a calibrated centrifuge tube to a final volume of 1.0 milliliters for GC/MS analysis. Immediately prior to instrumental analysis, the sample is spiked with a deuterated internal standard to compensate for variations in injection volume, instrument conditions etc.

A.3 GC/MS Analysis of Extractables

A Finnigan 4510 GC/MS system was used for gas chromatographic/mass spectrometric analysis. The EPA consent decree base/neutral and acid extractable standards were used to establish instrumental sensitivity and to provide identification criteria for sample analysis. The conditions employed were as follows:

Gas Chromatography

Injection Mode	On-column
Column	30 m DB5 x 0.32 mm ID
Column Flow	He @ 20 cm/sec.

Oven Temperature Profile

60°C - 2 min.--

60°C--> 270°C @ 10°C/min. hold 15 min.

GC/MS Interface - Direct Couple

Transfer Ara - 270°C

Mass Spectrometry

Ionization Mode	Electron Impact
Electron Energy	70 eV
Filament Emission	0.5 A
Electron Multiplier	1200 V @ 1 x 106 Gain
Ionizer Temperature	170°C
Scan	45 - 550 a.m.u. @ .95S - .05S
	Bottom Hold

A.4 Total Organic Halogen (TOX)

"Standard Methods for the Examination of Water and

Wastewater, 16th edition, 1985". Method 506. Organic Halogen (Total) pp. 516 - 525, using a Dohrmann Instrument.

A.5 Total Organic Carbon (TOC)

"Standard Methods for the Examination of Water and Wastewater, 16th edition, 1985". Method 505A. Organic Carbon (Total) pp. 507 - 511.

A.6 Inorganic Analytical Methodology

All inorganic analyses were performed using "Standard Methods for the Examination of Water and Wastewater, 16th edition, 1985".

A.6.1 Metals

Method 305, Metals by Emission Spectroscopy Using an Inductively Couples Plasma Source (Tentative), pp. 180 - 182.

A.6.2 Anions

Method 429, Determination of Anions by Ion Chromaography with conductivity Measurement, pp. 483 - 488.

A.6.3 Chemical Oxygen Demand (COD)

Method 508 A. Oxygen Demand (Chemical), pp. 532-538.

A.6.4 **Biochemical Oxygen Demand (BOD)**

Method 507, Oxygen Demand (Biochemical), pp. 525-532.

A.6.5 **Total Suspended Solids (Group 8)**

Method 209 C, Total Suspended Solids Dried at 103-105°C, pp. 96-97.

A.6.6 **Total Dissolved Solids (Group 8)**

Method 209 B, Total Dissolved Solids Dried at 180°C, pp. 95-96.

A.6.7 **Alkalinity**

Method 403, Alkalinity, pp. 269-273.

APPENDIX B

ANALYTICAL RESULTS FOR ORGANICS

Table B.1
Extractable Organic Analytical Results

Parameter	MDL	Raw Feed 17 July'87	Raw Feed 17 Sept'87	MF Permeate *	Method Blank
Acenaphthylene	0.1	ND	ND	ND	ND
Acenaphthene	0.1	ND	ND	ND	ND
Anthracene	0.1	ND	ND	ND	ND
Aldrin	1	ND	ND	ND	ND
Benzidine	0.1	ND	ND	ND	ND
Benzo(a)anthracene + Chrysene*	0.1	ND	ND	ND	ND
Benzo(b+k)fluoranthene	0.1	ND	ND	ND	ND
Benzo(a)pyrene	0.1	ND	ND	ND	ND
Benzo(ghi)perylene	0.1	ND	ND	ND	ND
Benzylbutyl phthalate	0.1	ND	ND	ND	ND
alpha-BHC	1	ND	ND	ND	ND
beta-BHC	1	ND	ND	ND	ND
gamma-BHC	1	ND	ND	ND	ND
Bis(2-chloroethyl)ether	0.1	ND	ND	ND	ND
Bis(2-chloromethyl)methane	0.1	ND	ND	ND	ND
Bis(2-ethylhexyl)phthalate	0.1	0.60	0.35	0.37	ND
Bis(2-chloroisopropyl)ether	0.1	ND	ND	ND	ND
4-Bromodiphenylether	0.1	ND	ND	ND	ND
Chlordane	1	ND	ND	ND	ND
4-Chlorodiphenylether	0.1	ND	ND	ND	ND
Chrysene	0.1	ND	ND	ND	ND
p,p'-DDD	1	ND	ND	ND	ND
p,p'-DDE	1	ND	ND	ND	ND
p,p'-DDT	1	ND	ND	ND	ND
Dibenzo(a,h)anthracene	0.1	ND	ND	ND	ND
Di-n-butyl phthalate	0.1	ND	ND	ND	ND
Di-n-octyl phthalate	0.1	0.34	ND	ND	ND
1,2-Dichlorobenzene	0.1	ND	ND	ND	ND
1,3-Dichlorobenzene	0.1	ND	ND	ND	ND
1,4-Dichlorobenzene	0.1	ND	ND	ND	ND
3,3'-Dichlorobenzidine	0.1	ND	ND	ND	ND
Dieldrin	1	ND	ND	ND	ND
Diethyl phthalate	0.1	1.1	0.85	ND	ND
Dimethyl phthalate	0.1	ND	ND	ND	ND
2,4-Dinitrotoluene	1	ND	ND	ND	ND
2,6-Dinitrotoluene	1	ND	ND	ND	ND
Endosulfan I	1	ND	ND	ND	ND
Endosulfan II	1	ND	ND	ND	ND
Endosulfan Sulfate	1	ND	ND	ND	ND
Endrin	1	ND	ND	ND	ND
Endrin aldehyde	1	ND	ND	ND	ND
Fluoranthene	0.1	ND	ND	ND	ND
Fluorene	0.1	ND	ND	ND	ND
Heptachlor	1	ND	ND	ND	ND
Heptachlor epoxide	1	ND	ND	ND	ND
Hexachlorobenzene	0.1	ND	ND	ND	ND
Hexachlorobutadiene	0.1	ND	ND	ND	ND
Hexachlorocyclopentadiene	0.1	ND	ND	ND	ND

Table B.1
Extractable Organic Analytical Results

Parameter	MDL	Raw Feed 17 July'87	Raw Feed 17 Sept'87	MF Permeate *	Method Blank
Hexachloroethane	0.1	ND	ND	ND	ND
Indeno(1,2,3-cd)pyrene	0.1	ND	ND	ND	ND
Isophorone	0.1	ND	ND	ND	ND
Naphthalene	0.1	ND	ND	ND	ND
Nitrobenzene	0.1	ND	ND	ND	ND
N-Nitrosodi-N-Propylamine	0.1	ND	ND	ND	ND
N-Nitrosodimethylamine	0.1	ND	ND	ND	ND
N-Nitrosodiphenylamine	0.1	ND	ND	ND	ND
PCB-1016	2	ND	ND	ND	ND
PCB-1221	2	ND	ND	ND	ND
PCB-1232	2	ND	ND	ND	ND
PCB-1242	2	ND	ND	ND	ND
PCB-1248	2	ND	ND	ND	ND
PCB-1254	2	ND	ND	ND	ND
PCB-1260	2	ND	ND	ND	ND
Phenanthrene	0.1	ND	ND	ND	ND
Pyrene	0.1	ND	ND	ND	ND
Toxaphene	10	ND	ND	ND	ND
1,2,4-Trichlorobenzene	0.1	ND	ND	ND	ND
4-Chloro-3-methylphenol	0.5	ND	ND	ND	ND
2-Chlorophenol	0.5	ND	ND	ND	ND
2,4-Dichlorophenol	0.5	ND	ND	ND	ND
2,4-Dimethylphenol	0.5	ND @ 10	ND @ 6	ND @ 2	ND
2,4-Dinitrophenol	0.5	ND	ND	ND	ND
2-Methyl-4,6-dinitrophenol	0.5	ND	ND	ND	ND
2-Nitrophenol	0.5	ND	ND	ND	ND
4-Nitrophenol	0.5	ND	ND	ND	ND
Pentachlorophenol	0.5	ND	ND	ND	ND
Phenol	0.5	5.3	3.9	1.1	ND
2,4,6-Trichlorophenol	0.5	ND	ND	ND	ND
Surrogate Recovery %					
d10-Anthracene		Dilution!	Dilution!	Dilution!	121
d3-Dichlorophenol		Dilution!	Dilution!	Dilution!	116

* MF permeate generated in the Microfiltration Pretreatment testing (Section 4.3) and results discussed in Section 5.3

Table B.2
Volatile Organic Analytical Results

Parameter	MDL	Raw Feed 17 Sept'87	MF Permeate *	Method Blank
Chloromethane	40	ND	ND	ND
Vinyl Chloride	40	ND	ND	ND
Bromomethane	40	ND	ND	ND
Chloroethane	20	ND	ND	ND
Trichlorofluoromethane	3.0	ND	ND	ND
1,1-Dichloroethene	3.0	ND	ND	ND
Methylene chloride	3.0	72	150	34
trans-1,2-Dichloroethene	3.0	4.1	ND	ND
1,1-Dichloroethane	3.0	60	ND	ND
Chloroform	3.0	ND	ND	ND
1,1,1-Trichloroethane	3.0	ND	ND	ND
1,2-Dichloroethane	3.0	5.9	ND	ND
Carbon tetrachloride	3.0	ND	ND	ND
Benzene	3.0	7.1	ND	ND
1,2-Dichloropropane	3.0	ND	ND	ND
Trichloroethene	3.0	Tr	ND	ND
Bromodichloromethane	3.0	ND	ND	ND
2-Chloroethylvinyl ether	10	ND	ND	ND
cis-1,3-Dichloropropene	3.0	ND	ND	ND
Toluene	3.0	79	36	ND
trans-1,3-Dichloropropene	3.0	ND	ND	ND
1,1,2-Trichloroethane	3.0	ND	ND	ND
Dibromochloromethane	3.0	ND	ND	ND
Tetrachloroethene	3.0	8.1	ND	ND
Chlorobenzene	3.0	ND	ND	ND
Ethylbenzene	3.0	4.2	3.3	ND
Bromoform	3.0	ND	ND	ND
1,1,2,2-Tetrachloroethane	3.0	ND	ND	ND
Surrogate Recoveries (%)				
Bromochloromethane		101	96	101
1,4-Difluorobenzene		105	91	103
d5 Chlorobenzene		59	88	97

ND = Not Detected
MDL = Minimum detection limits
Tr=Trace

* MF permeate generated in the Microfiltration Pretreatment testing (Section 4.3) and results discussed in Section 5.3

Table B.3
Extractable Organic Analytical Results

Parameter (Units in ug/L)	MDL	Spiked RO Feed	Filmtec Permeate (Test 3)	Method Blank
Acenaphthylene	1	ND	ND	ND
Acenaphthene	1	ND	ND	ND
Anthracene	1	ND	ND	ND
Aldrin	10	ND	ND	ND
Benzidine	5	ND	ND	ND
Benzo(a)anthracene	1	ND	ND	ND
Benzo(b+k)fluoranthene	1	ND	ND	ND
Benzo(a)pyrene	1	ND	ND	ND
Benzo(ghi)perylene	1	ND	ND	ND
Benzylbutyl phthalate	1	ND	ND	ND
alpha-BHC	10	ND	ND	ND
beta-BHC	10	ND	ND	ND
gamma-BHC	10	ND	ND	ND
Bis(2-chloroethyl)ether	1	ND	ND	ND
Bis(2-chloromethyl)methane	1	ND	ND	ND
Bis(2-ethylhexyl)phthalate	1	2.4	ND	ND
Bis(2-chloroisopropyl)ether	1	ND	ND	ND
4-Bromodiphenylether	1	ND	ND	ND
Chlordane	10	ND	ND	ND
2-Chloronaphthalene	1	ND	ND	ND
4-Chlorodiphenylether	1	ND	ND	ND
Chrysene	1	ND	ND	ND
p,p'-DDD	10	ND	ND	ND
p,p'-DDE	10	ND	ND	ND
p,p'-DDT	10	ND	ND	ND
Dibenzo(a,h)anthracene	1	ND	ND	ND
Di-n-butyl phthalate	1	2.4	ND	ND
Di-n-octyl phthalate	1	ND	ND	ND
1,2-Dichlorobenzene	1	ND	1.4	ND
1,3-Dichlorobenzene	1	ND	ND	ND
1,4-Dichlorobenzene	1	ND	ND	ND
3,3'-Dichlor[illegible]tine	10	ND	ND	ND
Dieldrin	10	ND	ND	ND
Diethyl phthalate	2	ND	ND	ND
Dimethyl phthalate	2	ND	ND	ND
2,4-Dinitrotoluene	2	ND	ND	ND
2,6-Dinitrotoluene	2	ND	ND	ND
Endosulfan I	10	ND	ND	ND
En[illegible]sulfan II	10	ND	ND	ND
Endosulfan Sulfate	10	ND	ND	ND
Endrin	10	ND	ND	ND
Endrin aldehyde	10	ND	ND	ND
Fluoranthene	1	ND	ND	ND
Fluorene	1	ND	ND	ND
Heptachlor	10	ND	ND	ND
Heptachlor epoxide	10	ND	ND	ND
Hexachlorobenzene	1	ND	ND	ND
Hexachlorobutadiene	2	ND	ND	ND

Table B.3
Extractable Organic Analytical Results

Parameter (Units in ug/L)	MDL	Spiked RO Feed	Filmtec Permeate (Test 3)	Method Blank
Hexachlorocyclopentadiene	2	ND	ND	ND
Hexachloroethane	2	ND	ND	ND
Indeno(1,2,3-cd)pyrene	1	ND	ND	ND
Isophorone	5	ND	ND	ND
Naphthalene	1	ND	ND	ND
Nitrobenzene	1	ND	ND	ND
N-Nitrosodi-N-Propylamine	1	ND	ND	ND
N-Nitrosodimethylamine	1	ND	ND	ND
N-Nitrosodiphenylamine	1	ND	ND	ND
PCB-1016	10	ND	ND	ND
PCB-1221	10	ND	ND	ND
PCB-1232	10	ND	ND	ND
PCB-1242	10	ND	ND	ND
PCB-1248	10	ND	ND	ND
PCB-1254	10	ND	ND	ND
PCB-1260	10	ND	ND	ND
Phenanthrene	1	ND	ND	ND
Pyrene	1	ND	ND	ND
Toxaphene	10	ND	ND	ND
1,2,4-Trichlorobenzene	1	ND	ND	ND
4-Chloro-3-methylphenol	1	ND	ND	ND
2-Chlorophenol	1	ND	ND	ND
2,4-Dichlorophenol	1	ND	ND	ND
2,4-Dimethylphenol	1	ND	ND	ND
2,4-Dinitrophenol	1	ND	ND	ND
2-Methyl-4,6-dinitrophenol	1	ND	ND	ND
2-Nitrophenol	3	ND	ND	ND
4-Nitrophenol	3	ND	ND	ND
Pentachlorophenol	0.5	1000	0.8	ND
Phenol	1	430	30	ND
2,4,6-Trichlorophenol	1	ND	ND	ND
Surrogate Recovery %				
d10-Anthracene		109	107	60
d3-Dichlorophenol		137	104	64
d12-Benzo(a)pyrene		111	161	85

* Spiked RO Feed and Filmtec permeate generated in the Configured Membrane testing (Section 4.5) and results discussed in Section 5.5

Table B.4
Volatile Organic Analytical Results

Parameter	MDL	Raw Feed 19 Jan'88	MF Permeate *	Filmtec Permeate (Test 3)	Method Blank
Chloromethane	5.0	ND	ND	ND	ND
Vinyl Chloride	1.0	ND	ND	ND	ND
Bromoethane	1.0	ND	ND	ND	ND
Chloroethane	5.0	ND	ND	ND	ND
Trichlorofluoromethane	1.0	ND	ND	ND	ND
1,1-Dichloroethene	1.0	27	2.2	ND	ND
Methylene chloride	NA	NA	NA	NA	NA
trans-1,2-Dichloroethene	1.0	ND	ND	ND	ND
1,1-Dichloroethane	1.0	100	7.2	ND	ND
Chloroform	1.0	41	ND	5.5	ND
1,1,1-Trichloroethane	1.0	ND	ND	ND	ND
1,2-Dichloroethane	1.0	100	2.7	ND	ND
Carbon tetrachloride	1.0	ND	ND	ND	ND
Benzene	1.0	59	5.7	110	ND
1,2-Dichloropropane	1.0	ND	ND	ND	ND
Trichloroethene	1.0	12	ND	ND	ND
Bromodichloromethane	1.0	3	ND	3.2	ND
2-Chloroethylvinyl ether	1.0	ND	ND	ND	ND
cis-1,3-Dichloropropene	1.0	ND	ND	ND	ND
Toluene	1.0	550	320	100	ND
trans-1,3-Dichloropropene	1.0	ND	ND	ND	ND
1,1,2-Trichloroethane	1.0	ND	ND	ND	ND
Dibromochloromethane	1.0	ND	ND	ND	ND
Tetrachloroethene	1.0	ND	ND	ND	ND
Chlorobenzene	1.0	30	ND	ND	ND
Ethylbenzene	1.0	79	1.5	140	ND
Bromoform	1.0	ND	ND	ND	ND
1,1,2,2-Tetrachloroethane	1.0	ND	ND	ND	ND
Dilution Factor		5	1	10	1

Note: Detection limits should be multiplied by dilution factor

Surrogate Recoveries (%)

D4 DCA	98	95	101	117
D8 Toluene	85	93	89	24
BFB	85	91	111	85

ND = Not Detected
MDL = Minimum detection limits
NA = Not Analyzed

* MF permeate (spiked with toluene and pentachlorophenol) and Filmtec permeate generated in the Configured Membrane testing (Section 4.5), results discussed in Section 5.5

APPENDIX C

DESIGN SPECIFICATIONS FOR COST ANALYSIS

TABLE C.1

DESIGN SPECIFICATIONS FOR LEACHATE TREATMENT PROCESS

Capacity (liters/day)	56,775	113,550	170,325
Capacity (USGFD/day)	15,000	30,000	45,000

Chemical Reaction System

System to Include: 1) Reaction Tank, 2) Mixer, 3) Chemical Storage Tanks, 4) Chemical Metering System and 5) pH probe, level switches and controls.

Lime Dosage (g/L)	3.0	3.0	3.0
Lime Required (kg/yr)	62,169	124,337	186,506
Soda Ash Dosage (g/L)	1.5	1.5	1.5
Soda Ash Required (kg/yr)	31,084	62,169	93,253
Reaction Tank Size (usgal)	150	300	450
Tank Retention Time (min)	14	14	14
Chemical Reaction System Cost ($)	$15,000	$17,000	$19,000

Micro Filtration System

System to include: 1) Process Pump, 2) Membrane Modules, 3) CIP Tank, 4) interconnecting piping and 5) Meters and Controls

System Recovery	85%	85%	85%
Productive Operating Time	75%	75%	75%
Permeate Required (gpd)	17,000	34,000	51,000
Assumed Flux (gfd)	75	75	75
Membrane Area (sq. ft.)	227	453	680
Pump HP	10	20	31
MF System Cost ($)	$46,013	$74,800	$95,200

TABLE C.1 (continued)

DESIGN SPECIFICATIONS
FOR LEACHATE TREATMENT PROCESS

Capacity (liters/day)	56,775	113,550	170,325
Capacity (USGFD/day)	15,000	30,000	45,000

Filter Press

Includes semi automatic plate and frame filter press with controls.

Solids Loading (cubic ft/day)	10-12	20-24	30-36
Capacity (cubic ft)	6.3	12.6	18.9
Filter Cost ($)	$27,500	$43,152	$56,164

RO System

System to include: 1) Process Pump, 2) Membrane Modules, 3) CIP Tank, 4) interconnecting piping and 5) Meters and Controls

System Recovery	50%	50%	50%
Productive Operating Time	75%	75%	75%
Permeate Required (gpd)	10,000	20,000	30,000
Assumed Flux (gfd)	16	16	16
Membrane Area (sq. ft.)	625	1,250	1,875
Pump HP	25	50	75
RO System Cost ($)	$36,169	$56,525	$78,094

TABLE C.2

COST BASIS FOR COMMODITIES

Lime ($/Kg)*	$0.074
Soda Ash ($/Kg)*	$0.23
Power ($/KW)	$0.0135
Labour ($/hr)	$25.00

* Delivered Cost on a one metric tonne basis, 1988 $CDN.

APPENDIX D

RAW DATA FOR EXPERIMENTAL WORK

Pretreatment Screening
Test 1

Time (hours)	Inlet Pressure (psi)	Outlet Pressure (psi)	Temp ('C)	Concentrate Flowrate (lpm)	MF2 Permeate Flux (usgfd)
0.00	33	25	22.5	12	
0.17					79
0.32					52
0.50	33	25	23	12	47
0.67					41
1.00	33	25	23	12	33
1.17					32
1.32					32
1.67	33	25	24	12	31
1.84					34
2.00			43		38
2.25	32	25	33	12	30
2.42			29		25
2.67	33	25	28	12	21
2.92	33	25	26		23
3.17	33	25	27	12	21
3.42	33	25	27		19

Note: Pretreatment 1 involved addition of caustic to pH 10 before microfiltration.

Pretreatment Screening
Test 2

Time (hours)	Inlet Pressure (psi)	Outlet Pressure (psi)	Temp ('C)	Concentrate Flowrate (lpm)	MF2 Permeate Flux (usgfd)
0.00	34	27	26	12	296
0.17					279
0.32	34	27	25		256
0.50					250
0.67	34	27	25		243
0.84					228
1.00	34	27	25		225
1.17					218
1.32	34	26	25	12	209
1.50					169
1.67	33	25	26	12	165
1.84					162
2.00	33	25	26	12	162
2.17	33	25	26		154
2.32					154
2.50	33	25	25		156
2.67					156
2.84	33	25	26		158
3.00	33	25	26		161
3.25	35	25	26	16	138
3.50	35	25	26	16	165
3.75				16	165

Note: Pretreatment 2 involved addition of lime to pH 10 before microfiltration

Pretreatment Screening
Test 3

Time (hours)	Inlet Pressure (psi)	Outlet Pressure (psi)	Temp ('C)	Concentrate Flowrate (lpm)	MF2 Permeate Flux (usgfd)
0.00	35	27		13	99
0.17					98
0.32					102
0.50	35	27	26	13	101
0.67					100
0.84	35	27	26	13	102
1.00					106
1.17					105
1.32					107
1.50	35	27	26	13	106
1.67					106
1.84					108
2.00	35	29	26	13	114
2.17					110
2.50	35	29	26	13	114
2.67					106
2.92					108
3.00	35	27	26	13	108

Note: Pretreatment 3 involved addition of lime to pH 10 and 600 g of powdered activated carbon to 30 L. of the leachate sample before microfiltration.

Microfiltration Pretreatment

Time (hours)	Perm Flux (usgfd)	% Volume Reduction
0	208	0%
0.25	213	0%
0.5	177	3%
0.75	184	5%
1	171	6%
1.25	159	7%
1.5	151	9%
2	167	11%
2.5	146	13%
3	113	16%
3.25	118	16%
3.5	106	17%
4	106	19%
4.25	102	20%
4.5	101	21%
5.5	91	24%
6.5	84	26%
7.25	79	28%
7.75	83	30%
8.75	83	32%
9.75	83	35%
10.75	85	37%
11.75	95	40%
12	121	41%
12.75	125	44%
13.5	89	46%
14	75	48%
15	98	50%
15.75	92	53%
16.75	97	56%
17.75	95	59%
18.75	98	62%
24.25	102	79%
24.5	116	80%
24.75	101	81%
26	66	84%
26.5	59	85%
27	59	86%
27.75	18	87%
28.25	21	87%
28.75	24	88%
29.25	21	88%
29.75	21	88%

Operating Parameters

Inlet Pressure 35 psig
Outlet Pressure 27 psig
Temperature ~ 27'c
System Flowrate 12 lpm
- 370 L of raw feed was initially used.
- 330 L of permeate produced
- 40 L of concentrate produced.

RO Screening
Pre-Saltwater Test

Flux Rates

Time (Hours)	Nitto (GFD)	Filmtec (GFD)	Desal (GFD)	Torray (GFD)
0	52	73	36.5	0
0.25	52	73	41.7	0
0.5	62.5	80.8	31.3	15.6
0.75	73	75.6	33.9	15.6
1	57.3	78.2	36.5	15.6
1.25	59.9	70.3	33.9	13
1.5	57.3	73	36.5	13
1.75	52	86	33.9	13
2	57.3	78.2	46.9	13
2.25	62.5	78.2	46.9	10.4
2.5	57.3	73	36.5	15.6
2.75	65.1	70.3	31.3	20.8
3	73	73	26	10.4

Conductivity Reading (mmhos) and % Rejection

Time (Hours)	Feed	Nitto		Filmtec		Desal		Torray	
1		0.211		0.074		0.111		0.160	
1.25	3.35	0.175	95%	0.060	98%	0.104	97%	0.106	97%
1.5	3.35	0.186	94%	0.060	98%	0.104	97%	0.081	98%
1.75	3.43	0.176	95%	0.058	98%	0.105	97%	0.056	98%
2	3.47	0.181	95%	0.065	98%	0.111	97%	0.045	99%
2.25	3.47	0.217	94%	0.071	98%	0.112	97%		
2.5	3.6	0.194	95%	0.062	98%	0.113	97%	0.039	99%
2.75	3.59	0.194	95%	0.061	98%	0.112	97%		
3	3.61	0.198	95%	0.061	98%	0.113	97%	0.031	99%

Operating Parameters:

Pressure In 420 psig
Pressure Out 320 psig
Temperature 70 F
Flowrate 10 Lpm
Note: the flowrates have been pressure corrected.

RO Screening
Stability Test

Flux (GFD)

Time (Hours)	Nitto (GFD)	Filmtec (GFD)	Desal (GFD)	Torray (GFD)
0	44	37	29	5
0.25	44	37	29	8
0.5	38	45	31	9
0.75	44	47	29	5
1	37	47	27	9
1.25	47	39	31	11
1.5	42	39	31	11
1.75	42	39	29	9
2	37	39	34	14
5	44	37	29	13
5.25	39	39	27	11
5.5	39	29	29	11
15.25	35	26	22	5
15.75	37	29	24	8
16.75	42	37	24	5
18.75	30	29	27	5
19.75	33	26	22	7
20.75	28	29	22	10
21.75	27	24	19	10
23	35	25	20	8
23.75	30	21	22	11
42	35	25	20	8
50.5	32	24	24	9
89	31	19	22	7
90.5	34	20	18	8
91.25	27	21	22	9

Conductivity Readings (mmhos) and % Rejection

Time (Hours)	Feed	Nitto		Filmtec		Desal		Torray	
0.25	8.3	0.81	90.2%	0.33	96.0%	0.336	96.0%	0.16	98.1%
0.5	8.55	0.668	92.2%	0.22	97.4%	0.293	96.6%	0.19	97.8%
0.75	8.6	0.626	92.7%	0.209	97.6%	0.276	96.8%	0.22	97.4%
1.25	8.17	0.55	93.3%	0.186	97.7%	0.226	97.2%	0.208	97.5%
1.75	8.18	0.583	92.9%	0.199	97.6%	0.24	97.1%	0.238	97.1%
5	8.36	0.555	93.4%	0.185	97.8%	0.232	97.2%	0.187	97.8%
5.25	8.34	0.565	93.2%	0.188	97.7%	0.23	97.2%	0.188	97.7%
5.5	8.3	0.585	93.0%	0.195	97.7%	0.232	97.2%	0.23	97.2%
15.75	8.85	0.632	92.9%	0.169	98.1%	0.228	97.4%	0.178	98.0%
18.75	9.44	0.583	93.8%	0.170	98.2%	0.236	97.5%	0.189	98.0%
20.75	9.05	0.587	93.5%	0.167	98.2%	0.231	97.4%	0.175	98.1%
23.75	9.5	0.698	93.1%	0.195	97.9%	0.257	97.3%	0.204	97.9%
42	10.08	0.706	93.4%	0.193	98.1%	0.269	97.3%	0.192	98.1%
50.5	10.7	0.708	93.7%	0.195	98.2%	0.272	97.5%	0.227	97.9%
89	11.17	0.714	93.6%	0.180	98.4%	0.280	97.5%	0.207	98.1%
90.5	11.25	0.797	92.9%	0.202	98.2%	0.318	97.2%	0.237	97.9%

Operating Parameters:

Pressure In 420 psig
Pressure Out 320 psig
Temperature 70 F
Flowrate 10 Lpm
Note:the flowrates have been pressure corrected.

RO Screening
Post-Saltwater Test

Flux Rates

Time (Hours)	Nitto (GFD)	Filmtec (GFD)	Desal (GFD)	Torray (GFD)
0	39	36	30	9
0.25	42	37	31	10
0.5	39	32	29	14
0.75	42	34	28	12
1	39	34	29	11
1.25	42	33	27	11
1.5	42	34	31	9
1.75	42	34	28	12
2	42	34	31	12
2.25	42	36	29	11
2.5	43	34	30	14

Conductivity Readings (mmhos) and % Rejection

Time (Hours)	Feed	Nitto		Filmtec		Desal		Torray	
0	3.63	0.155	96%	0.054	99%	0.064	98%	0.105	97%
0.5	3.63	0.167	95%	0.05	99%	0.052	99%	0.037	99%
1	3.6	0.174	95%	0.048	99%	0.047	99%	0.027	99%
1.5	3.63	0.179	95%	0.048	99%	0.045	99%	0.023	99%
2	3.68	0.177	95%	0.046	99%	0.044	99%	0.021	99%
2.5	3.66	0.177	95%	0.046	99%	0.042	99%	0.016	100%

Operating Parameters:

Pressure In 420 psig
Pressure Out 320 psig
Temperature 70 F
Flowrate 10 Lpm
Feed: 2.5 g of salt per liter of RO water
Note:the flowrates have been pressure corrected.

Configured Membrane Testing
Microfiltration Pretreatment

Time (hours)	Perm Flux (usgfd)	% Volume Reduction
0	525.77	0%
0	402.06	0%
0.25	288.66	4%
1	180.41	13%
2	99.48	20%
3	99.48	25%
4.33	89.18	32%
5.33	82.47	36%
6.33	65.46	40%
6.6	61.86	41%
7	88.14	42%
7.2	61.86	43%
8	61.86	45%
9	53.09	48%
10	55.15	51%
11	55.15	54%
12	37.63	56%
13	51.03	59%
14	38.66	61%
15	48.45	63%
16	41.75	65%
18	35.05	69%
19	26.29	71%
20	41.75	72%
20.8	26.29	74%
21	59.79	74%
23.25	32.99	80%
24.75	51.03	83%
25.75	35.05	85%
27	41.75	87%
28.75	55.15	92%

Operating Parameters

Inlet Pressure 35 psig
Outlet Pressure 32 psig
Temperature ~ 17'c
System Flowrate 12 lpm
- 230 L of raw feed was initially used.
- 210 L of permeate produced
- 20 L of concentrate produced.

Configured Membrane Testing
Saltwater Flux Test
Pre-stability Test

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	2.21	27.90	0.48	78%	23.10	0.70	68%
0.25	1.95	27.85	0.48	76%	23.43	0.71	64%
0.50	1.95	28.08	0.48	75%	23.50	0.71	64%
0.75	1.94	27.90	0.48	75%	23.27	0.70	64%
1.00	1.95	27.50	0.47	76%	23.00	0.70	64%
1.25	1.95	28.08	0.48	75%	23.17	0.70	64%
1.50	1.94	28.67	0.49	75%	23.20	0.70	64%
1.75	1.95	28.08	0.48	75%	22.84	0.69	65%
2.00	1.95	27.50	0.47	76%	22.84	0.69	65%
Average		27.95		76%	23.15		65%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 220 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 200 psig
System Temperature: 70 'F

Saltwater Flux test
Post-stability Test

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	3.85	3.45	0.06	98%	8.47	0.26	93%
0.25	3.77	2.57	0.04	99%	8.11	0.25	94%
0.50	3.74	2.34	0.04	99%	7.84	0.24	94%
0.75	3.78	2.46	0.04	99%	7.58	0.23	94%
Average		2.71		99%	8.00		94%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 240 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 200 psig
System Temperature: 70 'F

Configured Membrane Testing
Stability Test

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	7.41	13.10	0.22	97%	28.47	0.86	88%
0.25	8.12	11.47	0.20	98%	24.86	0.75	91%
0.50	8.35	10.76	0.18	98%	23.67	0.72	91%
0.75	8.61	10.30	0.18	98%	23.50	0.71	92%
1.00	8.68	8.89	0.15	98%	21.95	0.66	92%
1.25	8.61	7.90	0.14	98%	20.59	0.62	93%
1.50	8.84	7.55	0.13	99%	20.56	0.62	93%
1.75	8.67	6.90	0.12	99%	19.96	0.60	93%
Average		9.61		98%	22.94		92%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 380 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 350 psig
System Temperature: 70 'F

Configured Membrane Testing
Concentration Test 1

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	8.24	19.89	0.24	97%	21.85	0.98	88%
0.08	8.64	19.89	0.23	97%	19.86	0.97	89%
0.25	9.16	18.02	0.26	97%	21.85	1.14	88%
0.42	11.11	17.55	0.29	97%	19.86	1.36	88%
0.58	12.05	16.85	0.33	97%	18.14	1.57	87%
0.75	13.05	15.80	0.32	98%	17.87	1.62	88%
1.25	13.53	16.38	0.28	98%	17.87	1.51	89%
1.75	13.64	16.38	0.25	98%	17.87	1.46	89%
2.75	13.88	15.21	0.21	98%	17.87	1.38	90%
3.75	13.76	16.38	0.19	99%	17.87	1.37	90%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 380 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 340 psig
System Temperature: 70 'F

Saltwater Flux test
Post-Concentration Test 1

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	3.87	14.04	0.05	99%	13.90	0.25	94%
0.25	3.86	14.39	0.05	99%	15.89	0.24	94%
0.50	3.86	14.39	0.03	99%	15.23	0.24	94%
0.75	3.84	14.63	0.03	99%	15.89	0.24	94%
Average		14.36		99%	15.23		94%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 240 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 200 psig
System Temperature: 70 'F

Configured Membrane Testing
Saltwater Flux test
Post-wash

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	2.22	14.04	0.06	97%	24.49	0.19	92%
0.25	2.30	15.21	0.02	99%	29.79	0.19	92%
0.50	2.30	15.21	0.02	99%	27.80	0.18	92%
0.75	2.33	15.21	0.02	99%	27.80	0.18	92%
1.00	2.30	15.21	0.02	99%	27.80	0.17	93%
1.25	2.30	15.21	0.02	99%	27.97	0.17	92%
Average		15.02		99%	27.61		92%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 240 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 200 psig
System Temperature: 70 F

Configured Membrane Testing
Concentration Test 2

Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	7.54	18.72	0.21	97%	33.76	1.51	80%
0.17	8.18	18.72	0.20	98%	31.78	1.55	81%
0.33	8.82	17.55	0.21	98%	30.45	1.72	80%
0.50	10.21	17.55	0.24	98%	29.13	2.07	80%
0.58	11.86	17.55	0.25	98%	27.80	2.26	81%
1.00	12.57	17.55	0.23	98%	26.48	2.41	81%
1.50	12.72	16.38	0.21	98%	26.48	2.44	81%
2.00	12.55	15.21	0.17	99%	26.48	2.34	81%
2.50	12.85	15.21	0.16	99%	26.48	2.23	83%
3.50	13.25	15.21	0.15	99%	26.48	2.17	84%

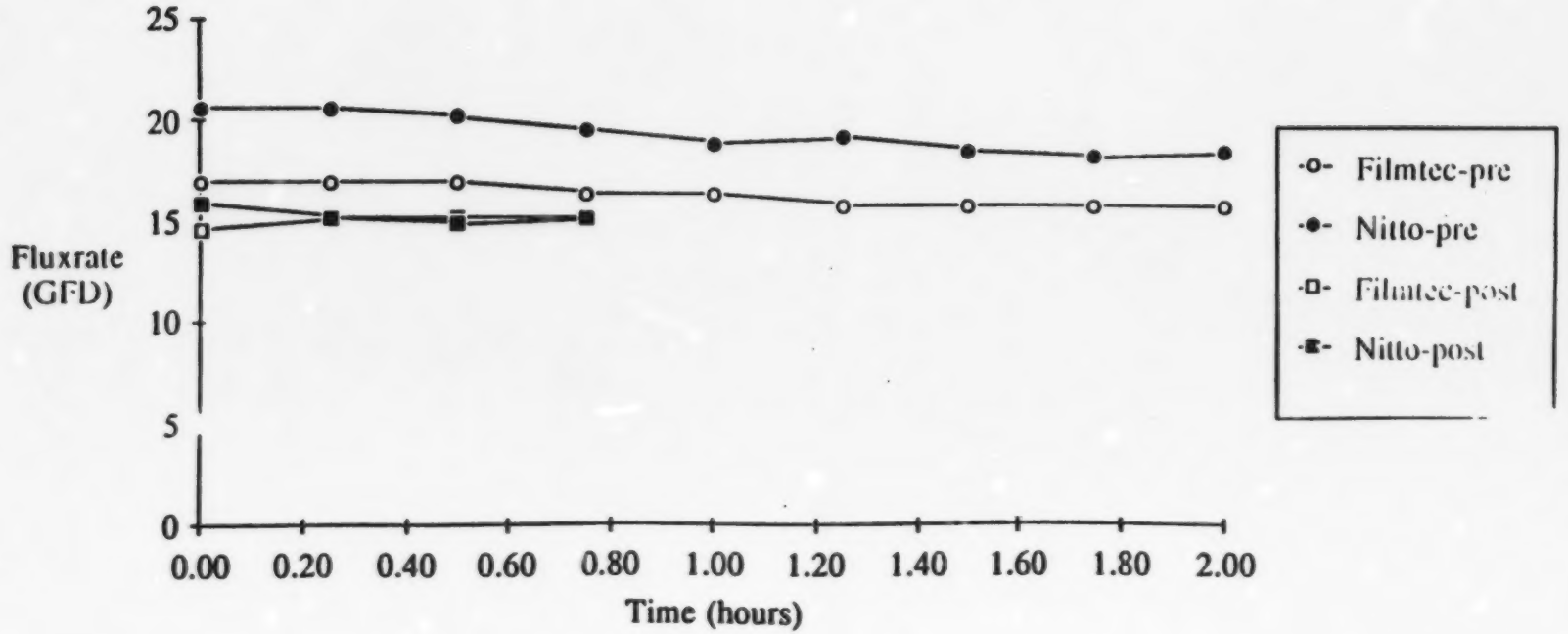
Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 380 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 340 psig
System Temperature: 70 'F

Saltwater Flux test
Post- concentration Test 2

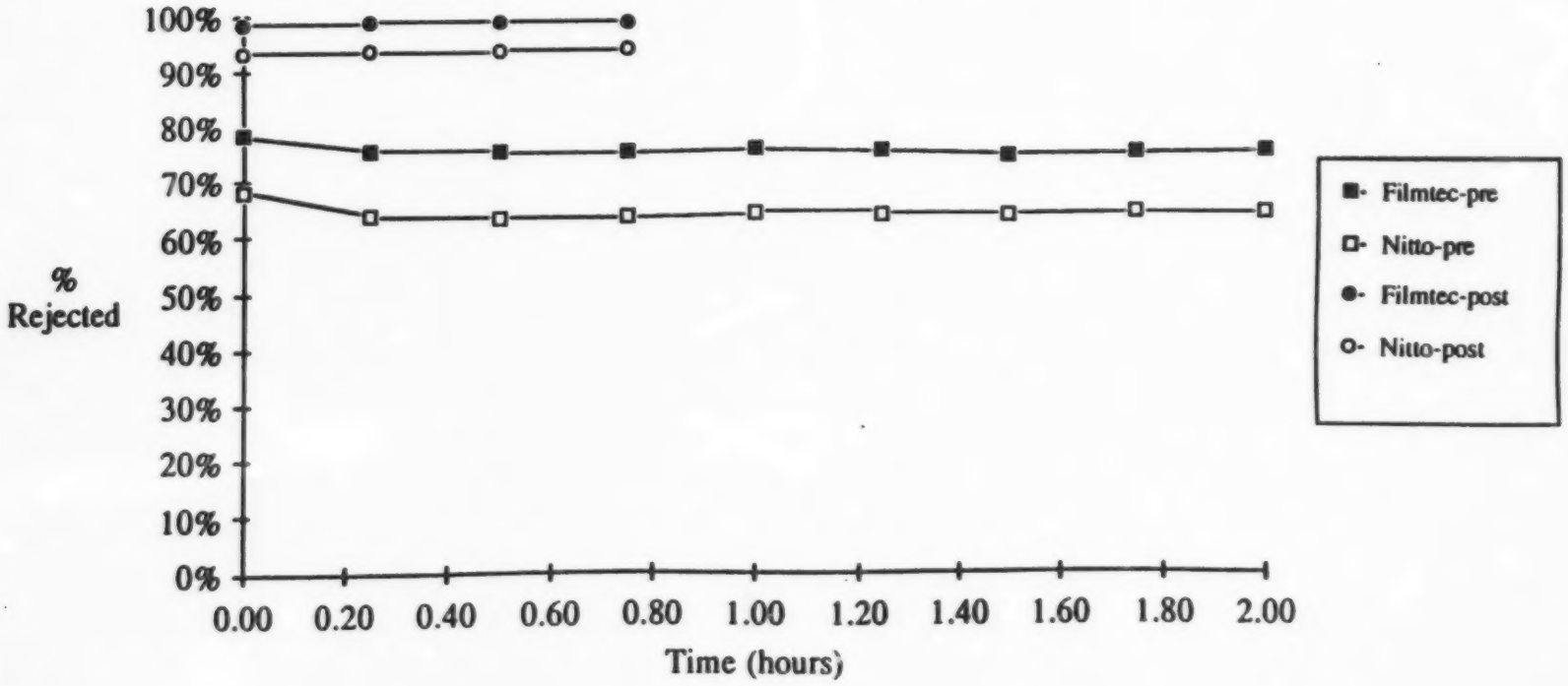
Time	Feed Cond	Filmtec Permeate Flow (GFD)	Filmtec Permeate Cond (mu)	Filmtec Permeate % Reject	Nitto Permeate Flow (GFD)	Nitto Permeate Cond (mu)	Nitto Permeate % Reject
0.00	4.47	11.70	0.12	97%	18.54	0.39	91%
0.25	3.92	14.04	0.04	99%	21.85	0.41	90%
0.50	3.86	14.04	0.04	99%	21.85	0.40	90%
0.75	3.92	14.04	0.03	99%	21.85	0.41	89%
Average		13.46		99%	21.02		90%

Operating Conditions:
Filmtec Concentrate Flow 18 LPM
Filmtec Outlet Pressure: 240 psig
Nitto Concentrate Flow 12 LPM
Nitto Outlet Pressure: 200 psig
System Temperature: 70 'F

Configured Membrane Test
Saltwater Flux for Stability Test 1

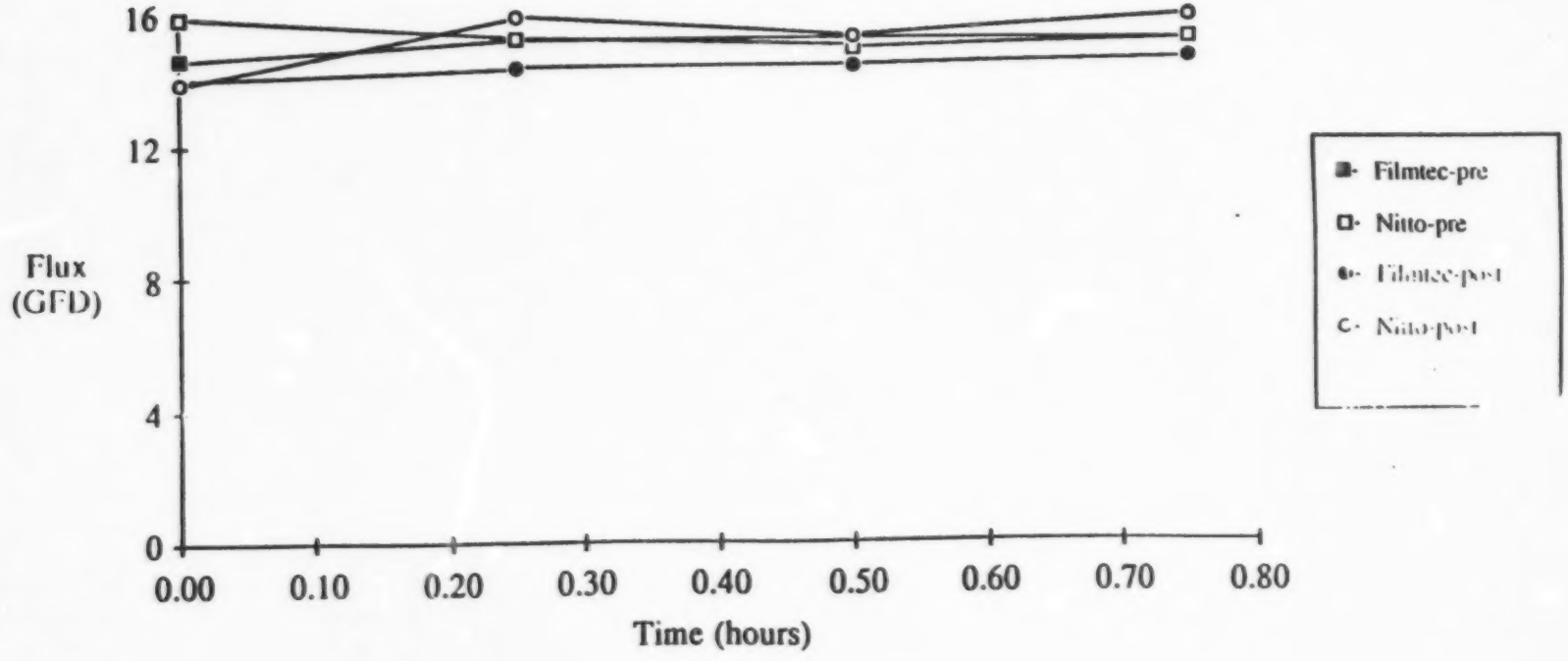


Configured Membrane Testing
% Rejection for Stability Test 1

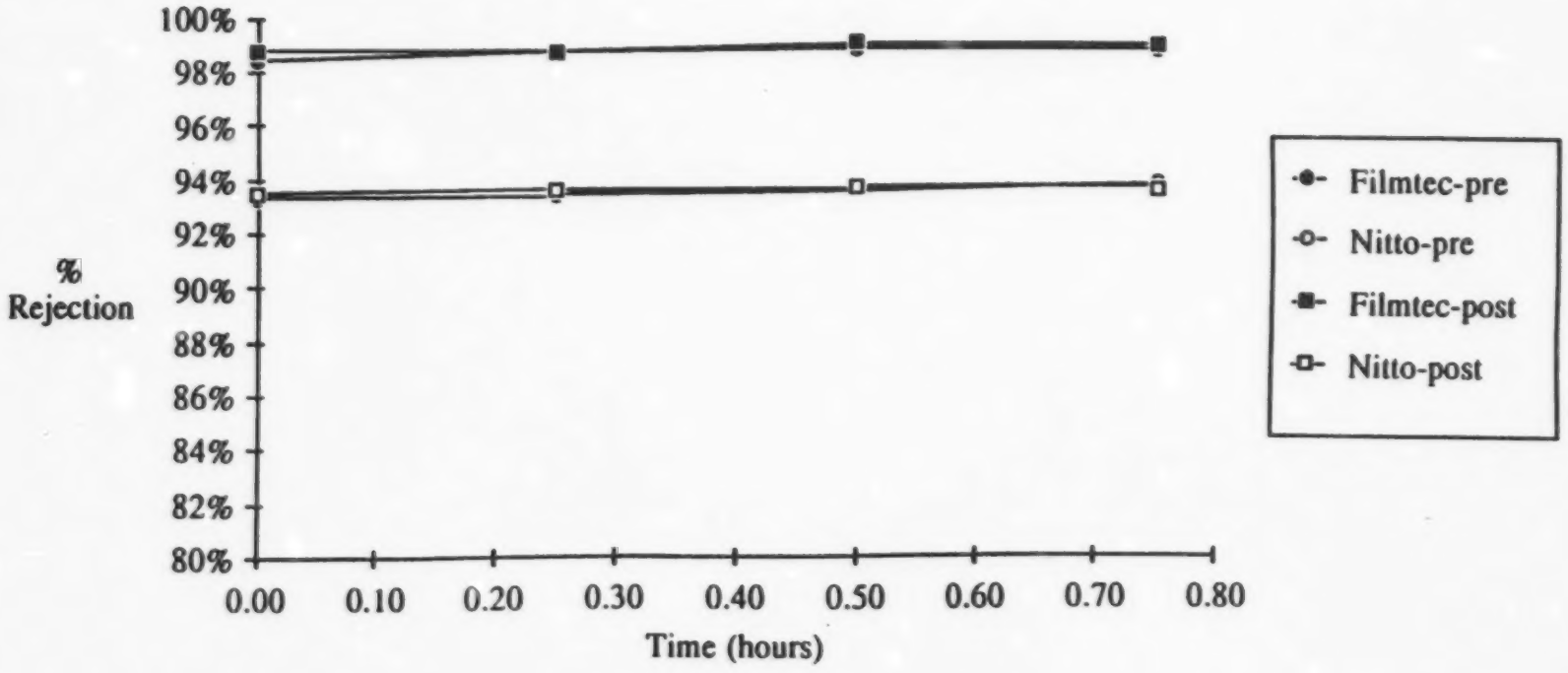


*Note: % Rejection based on conductivity

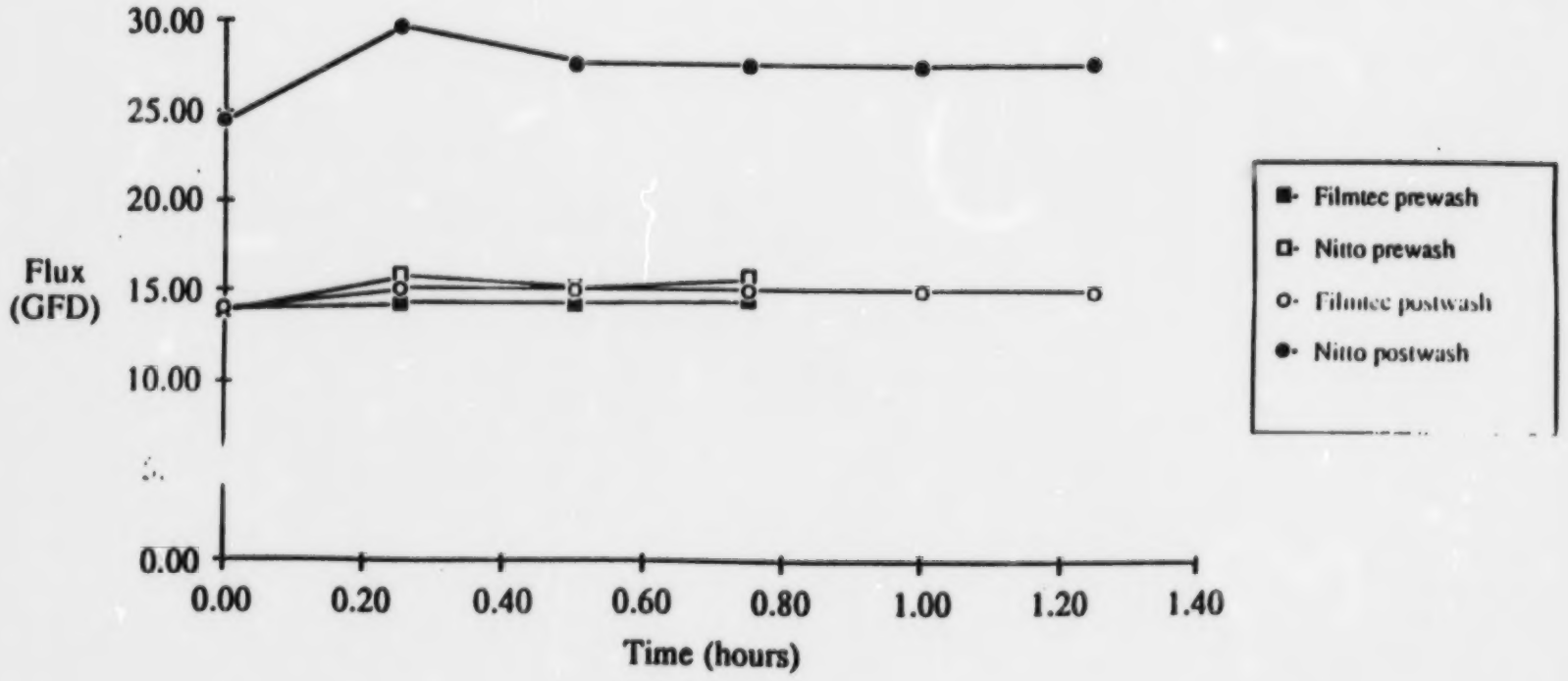
Configured Membrane Testing
Saltwater Flux for Concentration 1 Test

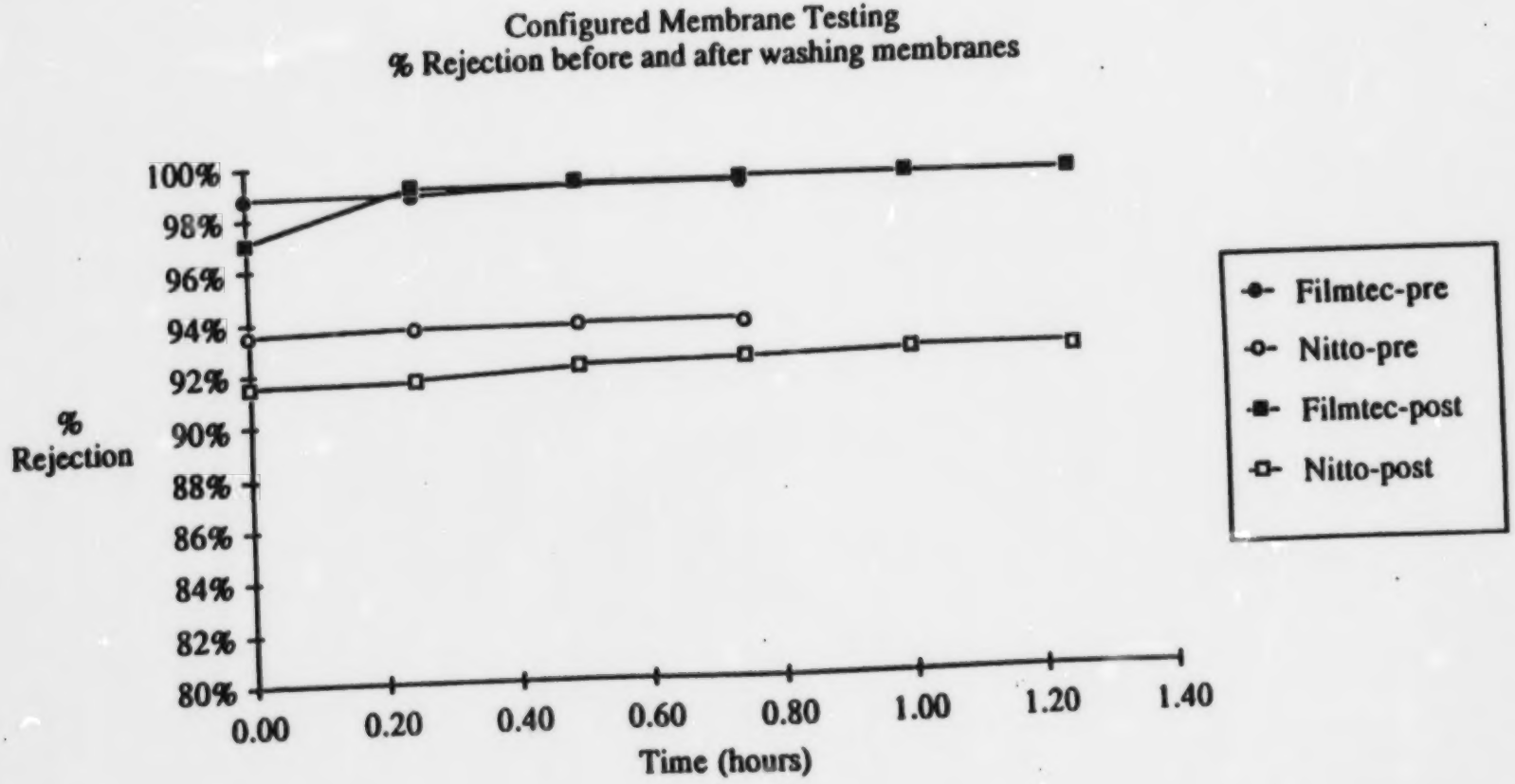


Configured Membrane Testing
% Rejection for Concentration 1 Test

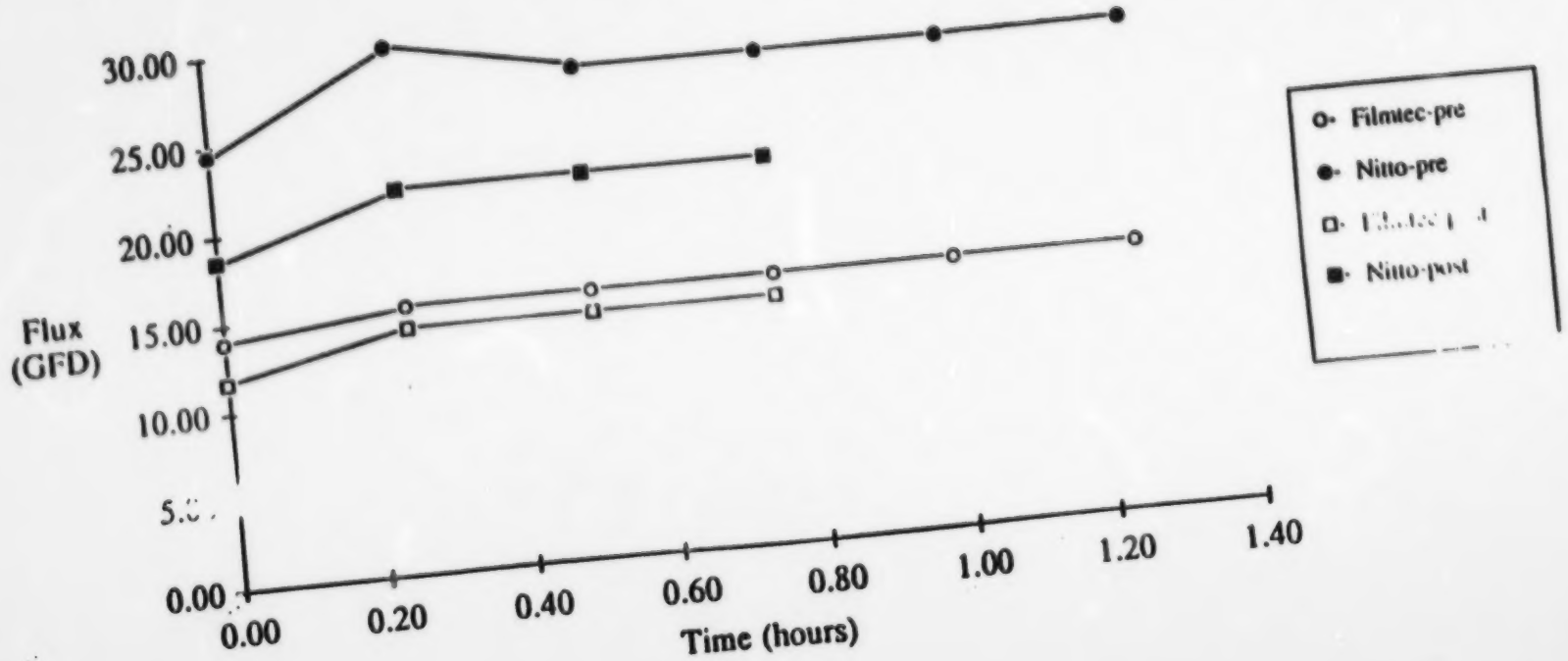


Configured Membrane Testing
Flux rate before and after washing membranes




Configured Membrane Testing
% Rejection before and after washing membranes
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
% Rejection
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
Time (hours)
Filmtec-pre
Nitto-pre
Filmtec-post
Nitto-post

Configur[illegible] Membrane Testing
Saltwater Flux for Concentration Test 2



Configured Membrane Testing
% Rejection for Concentration Test 2